# Roadmap to Resilient Ultra-Low Energy Built Environment with Deep Integration of Renewables in 2050:

## Proceedings, Montreal Symposium

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**Canadian Academy of Engineering**

Centre for Zero Energy Building Studies
Centre d'études sur le bâtiment à consommation nulle d'énergie

# Table of Contents

# Introduction

The Canadian Academy of Engineering (CAE) in collaboration with Concordia's Centre for Zero Energy Building Studies (CZEBS) hosted a **planning workshop on March 22, 2019 for a "Roadmap to Resilient Ultra-low Energy Built Environment with Deep Integration of Renewables in 2050"**. The workshop was co-chaired by the **Roadmap Co-Chairs and Fellows of CAE Andreas Athienitis and Andrew Pape-Salmon**. Following the workshop attended by about 25 thought leaders, a communique was published, summarized and updated below, followed by an overview of the Montreal 2020 meeting.

The Canadian Academy of Engineering (CAE) assembled Thought Leaders from the professional community, construction industry, academia and three levels of government to begin to work on a national "Roadmap to Resilient, Ultra-Low Energy Built Environment with Deep Integration of Renewables in 2050", with an aim to achieve at least an 80% reduction in greenhouse gas (GHG) emissions in new and existing buildings and associated community infrastructure. The CAE's Trottier Energy Futures Pathway project described scenarios for reducing energy supply emissions by up to 70% below 1990 levels across all energy uses, requiring an investment of 20-30% of Canada's non-residential business capital up to 2050. This represents a significant opportunity for diversification and economic growth. The CAE Roadmap will articulate resilient solutions for community planning, building form and design, existing building renewal, "smart" community energy infrastructure, and on-site renewable energy generation to provide a supplemental perspective on the Trottier project. These solutions could enable achievement of the 80% by 2050 goal, while simultaneously increasing the resilience of communities to acute shocks such as the **COVID19 pandemic**.

In recent history, we have experienced such shocks as the 1998 central/eastern Canada ice storm that resulted in up to a 5-week power cut, 4.7 million people displaced in Québec and Ontario and economic loss of over $6 billion. This led to significant damages to buildings after their occupants evacuated them due to utility outages, resulting in extensive water damage from frozen water pipes and contributing to the economic loss. Such damage could be greatly reduced through resilient solutions that enable on-site electricity and heat production with building-integrated renewables. We anticipate that climate change will increase prevalence and intensity of chronic stresses as well as acute shocks. We need to increase our resilience to these and other acute shocks, such as a catastrophic earthquake in British Columbia or the Yukon where much of the older building stock could be destroyed in some cities, depending on the location and scale of the event. Solutions that address the three objectives of resilience, deep reductions in GHG emissions, and optimized energy efficiency plus on-site renewables can future-proof buildings and infrastructure and maximize long-term economic benefits for building owners, occupants and society.

At the March 22 Thought Leaders' Workshop, we discussed many technological and systems solutions already demonstrated by leaders across Canada, including the Varennes Library in Québec, Canada's first institutional solar net-zero energy building. Inaugurated in 2016, this building is designed to produce approximately as much energy as it uses in an average year through a building-integrated photovoltaic system. In fact, the solar energy potential across most of the populated areas of Canada is significantly higher than most of northern Europe. Peak utility demand can be reduced through smart grids, with smart buildings being active participants to provide load flexibility and services to the grid, including short-term curtailment of water heaters, thermal storage on-site, and additional storage from electrical vehicles. Energy utility resource planning, consumption and production rate structures, and the development of building codes and standards will benefit from access to measured data from building operations, requiring information infrastructure aligned with privacy legislation.

The CAE and its partners have launched a major effort to consider many of the questions raised at the workshop, reflecting various constituencies represented, to identify practical technical, policy, standards development and institutional solutions, and to develop the Roadmap document by early 2022. The

Roadmap could be used by all levels of government, including Indigenous communities, the construction and real-estate industries, energy utilities, the associated professional communities, product manufacturers, academia, and other key influencers. The vision is for a resilient built environment that is economically optimized in design, operation, retrofit/renewal and energy over a long-term horizon equivalent to the lifetime of the building/infrastructure (at least 50 years).

Further research will build upon existing strong evidence that energy efficiency and on-site renewable energy generation are required for broader resilience of the building stock and associated community infrastructure. To accelerate the innovation cycle, we will look to reframe the problem statements, continue to learn from existing building operations, and enable "double-loop" learning. We will aim to integrate "silos" in the professional community (i.e., engineering, planning, architecture, real estate, and the administration and management of construction, buildings, utilities, governments and others). Finally, we will propose win-win approaches and solutions adapted to the different regional contexts for new and existing buildings and community energy infrastructure by identifying the design solutions that optimize the multiple objectives of building code objectives, energy efficiency, GHG reductions, on-site renewable energy generation and durability.

The Thought Leaders discussed concerns around the durability of modern construction, fuel and material choices, maintenance of existing affordable housing stock, procurement of professional services and "value engineering" (often cutting construction costs by installing lower performing components than envisioned in the design), market acceptance of innovative designs, management of risk and liability, and capacity of the industries to deliver solutions at scale. Consideration of key related barriers and research questions is being addressed through a network of leading Canadian researchers from about 15 universities across all major regions and over forty partners covering major stakeholders, including the built environment designers, energy utilities, municipalities, builders, and manufacturers.

The Roadmap will articulate existing and emerging societal goals, highlight all available government policy levers and market mechanisms, and provide at least three "pathways" to achieve the vision. Pathways are expected to include, but not limited to the following: evolving objectives for the national building code development system; adoption/ implementation of these codes by provinces, territories Indigenous communities and local governments; public/ industry awareness and education; opportunities through incentives/ insurance/ financing/ leadership investments; technical synergies of having buildings be active participants in the energy grids; energy pricing strategies for energy efficiency and models to facilitate integration of on-site renewable energy systems; qualification-based/ financial outcome-based (best net-present value design) construction procurement; alternative institutional frameworks, and community planning.

The Roadmap includes two major symposia – a mainly technically focused Symposium in Montreal in 2020 with papers from experts published as proceedings, followed by a policy focused Symposium in Victoria in 2021. The proceedings and discussions at the Montreal Symposium provide input to an Interim Roadmap Report to be completed by early 2021. In 2021, a symposium will be held in Victoria BC, focusing on policy solutions for all levels of government (local/regional, Indigenous, provincial, federal) that are analyzed and vetted by the CAE and partners, along with options for the roles and responsibilities of the key institutions that develop, implement and support building codes and standards, community energy infrastructure, and construction and building management. The resultant draft Roadmap will be posted by early 2022 with an opportunity for public input to the Canadian Academy of Engineering. It will be practical and digestible by layperson audiences and decision makers alike. It will provide multiple pathways that will appeal to the diversity of Canadian jurisdictions.

## **The Montreal Symposium and Proceedings**

This Symposium was held via webinar because of the COVID19 pandemic on October 16, 2020.

A technical committee was formed to organize the Symposium that will provide major input to the Roadmap through papers from experts and short presentations from key stakeholders, as well as discussion with the participants during the nearly 25 paper and panel presentations. The technical committee reviewed the papers, and the authors then implemented the comments of the reviewers in the final form included in these proceedings. The proceedings partly address the following **targets and key questions** identified in a position paper in the planning workshop of March 22, 2019, updated with the resilience challenges for the built environment to fight pandemics such as COVID19.

- How can Canada develop a bold but flexible plan (adaptable to different provincial energy contexts) to achieve the deep **80% reductions in GHG emissions** for new and existing buildings by designing for net-zero **resilient** communities for 2050? What are the pathways to achieve/approach this goal for existing communities? Some important solutions are discussed in the proceedings.
- A key approach in market transformation programs and policy **roadmaps** is often to lock in energy savings through progressively stringent energy codes and standards. What are the key barriers and opportunities to achieve this approach? It is recognized that the context is different in different regions/provinces and different pathways may be followed.
- How can future-drivers be incorporated into building designs and retrofits today, thereby enhancing the **resilience** against acute shocks and chronic stresses in the built environment and the associated community energy infrastructure?
- The **COVID19 pandemic** has further revealed the need for **resilient buildings** and their **ventilation systems** to be designed to limit the spread of viruses such as COVID19, which has been shown to be significantly spread as aerosols. This can be done by reducing recirculation of HVAC air and bringing in more fresh air to dilute pathogen concentration, thus limiting the spread of infections, in addition to use of special filters and UV disinfection measures. Canadian buildings need to be able to face crises such as ice-storms and pandemics simultaneously since both typically happen in winter; if they do, physically distancing with millions of people displaced from their homes and relocated in confined places/shelters will be very difficult, if not impossible, possibly resulting in many more deaths than what we experience with the COVID19 pandemic, particularly among vulnerable people.
- What is the role of **innovation and performance-based design**, versus a conservative approach that emphasizes prescriptive standards based on historic evidence and postpones consideration of probable design drivers such as climate change and other resilience factors?
- What can we learn from **transformative technologies such as low-emissivity windows that took nearly 30 years** for full adoption and how can the process of adoption be sped up for other transformative technologies such as building-integrated photovoltaics, cold-climate heat pumps, climate-responsive building materials (e.g., windows that can change solar heat gain depending on heating versus cooling loads), thermal and electrical storage, and smart predictive controls?
- What is the **optimal institutional framework** for advancing the aforementioned objectives, with respect to the national building and electrical code development system, provincial and territorial adoption in regulation, enforcement institutions (mainly local governments), professional reliance models, the “objective-based” premise of performance in building codes (despite continued adherence to prescriptive “acceptable-solutions”), and the opportunities for data-driven performance verification. What can we learn from other countries on innovation and resilience in building regulatory systems? What tweaks and comprehensive shifts could Canada benefit from?
- How can **integrated approaches for building design and operation, integration of on-site renewable energy generation, optimized interaction with smart grids, healthy and comfortable indoor environment** be developed and followed? This is a major challenge that cuts across major engineering disciplines and architecture/urban planning, as well as traditionally separate government departments.

# Roadmap to Resilient Ultra-Low Energy Built Environment with Deep Integration of Renewables in 2050: Symposium Program

Click on the paper title to open the selected paper and the presenter's name to open the biography.

| | | |
|---|---|---|
| **Online connection** | | 10:30 – 11:00 |
| **Graham Carr,** President and Vice-Chancellor of Concordia University | **Opening Remarks** | 11:00 – 11:05 |
| **Gina Cody, FCAE,** Gina Cody School of Engineering & Computer Science, Concordia University | **Welcoming Remarks** | 11:05 – 11:10 |
| **Andreas Athienitis, FCAE, Symposium Chair & Roadmap Co-Chair,** Director, Concordia Centre for Zero Energy Building Studies, Concordia University | **Introduction** | 11:10 - 11:20 |
| **Yves Beauchamp, FCAE/FACG, President CAE**, VP Administration and Finance, McGill University | **Background** | 11:20 - 11:30 |
| **PAPER SESSION I** | | |
| **PRESENTER** | **TITLE** | |
| **Miguel Anjos, FCAE,** Professor and Chair of Operational Research, School of Mathematics, **University of Edinburgh, U.K.** | Integration of Smart Buildings into the Electric Energy Grid | 11:35 - 11:40 |
| **Andreas Athienitis, FCAE,** Professor and NSERC/Hydro-Québec Industrial Research Chair & Concordia Chair, **Concordia University, QC** | Design and Operation of Resilient and Flexible Buildings | 11:40 - 11:45 |
| **Andrew Pape-Salmon, FCAE, Roadmap Co-Chair** Executive Director, Building and Safety Standards Branch, **Ministry of Municipal Affairs and Housing, BC** | Net-Zero Ready Building Codes | 11:45 - 11:50 |
| **Christopher Kennedy, FCAE,** Professor and Chair, Civil Engineering, **University of Victoria, BC** | Jurisdictional Responsibility for Improving the Resilience of Buildings to Climate-related Power Outages | 11:50 - 11:55 |
| **QUESTIONS** | | 11:55 - 12:10 |
| **Ursula Eicker,** Professor and Canada Excellence Research Chair, Building, Civil and Environmental Engineering, **Concordia University, QC** | Planning and Simulation of Net-Zero, Carbon Neutral and Resilient Communities | 12:10 - 12:15 |
| **Remi Charron,** Associate Professor, Energy Management, **New York Institute of Technology, BC** | Expanding Performance-Based Step-Codes Beyond Energy Efficiency using A Forward-Looking Reference Building | 12:15 – 12:20 |
| **Caroline Hachem-Vermette,** Associate Professor, Environmental Design, **University of Calgary, AB** | Design Strategies for Climate Resilient Neighborhoods | 12:20 – 12:25 |
| **Theodore Stathopoulos, FCAE,** Professor, Building, Civil, and Environmental Engineering, **Concordia University, QC** | Wind Resilience: Proceeding from Wind Codes and Standards of Building Design Practice | 12:25 - 12:30 |
| **QUESTIONS** | | 12:30 – 12:45 |

| BREAK | | 12:45 – 13:05 |
|---|---|---|
| **PAPER SESSION II** | | |
| **PRESENTER** | **TITLE** | |
| **Rosamund Hyde,** Manager of Research and Innovation Services, **Stantec, ON** | Building Operation and Occupant Behavior | 13:05 - 13:10 |
| **Ted Kesik,** Professor, Architecture, **University of Toronto, ON** | The Challenges of Developing Thermal Resilience Policies, Protocols and Procedures for Buildings | 13:10 – 13:15 |
| **Iain MacDonald,** Senior Research Officer, **National Research Council Canada, ON** | Supporting the Development of Net Zero Energy Ready Building Codes | 13:15 – 13:20 |
| **Liam O'Brien,** Associate Professor, Architectural Conservation and Sustainability Engineering, **Carleton University, ON** | A New Housing Stress Test: Codifying Thermal Resilience of Buildings | 13:20 - 13:25 |
| **Louis Gosselin**, Professor, Mechanical Engineering, **Laval University, QC** | Lessons Learned with Respect to the CAE Roadmap from the Monitoring of a High-Performance Social Housing Building in Quebec City | 13:25 – 13:30 |
| **QUESTIONS** | | 13:30 - 13:45 |
| **Chang-Seo Lee**, Research Associate, Building, Civil and Environmental Engineering, **Concordia University, QC** | Air Purification Technologies for Resilient Buildings: Abilities and Limitations | 13:45 – 13:50 |
| **Meli Stylianou,** Manager, Housing and Buildings R&D, **CANMET Energy, Natural Resources Canada, ON** | Pathways for Net Zero Energy Buildings and Communities Research Activities at Canmet Energy-Ottawa | 13:50 – 13:55 |
| **Marianne Touchie,** Assisant Professor, Civil Engineering and Mechanical & Industrial Engineering, **University of Toronto, ON** | Passive Strategies to Improve Multi-unit Residential Building Thermal Comfort Resilience in Future Climate Scenarios | 13:55 – 14:00 |
| **Costa Kapsis,** Assisant Professor, Civil and Environmental Engineering, **University of Waterloo, ON** | Building-Integrated Photovoltaic Systems: Enabling Energy-Resilient High-Performance Buildings | 14:00 – 14:05 |
| **Ian Beausoleil-Morrison,** Professor, Mechanical and Aerospace Engineering, **Carleton University, ON** | Providing the Majority of the Energy Needs of Canadian Housing by Solar: The Need for Seasonal Storage | 14:05 – 14:10 |
| **QUESTIONS** | | 14:10 – 14:25 |
| **BREAK** | | 14:25 – 14:30 |
| **PANEL DISCUSSION: Designing a Resilient Ultra-Low Energy Built Environment with Deep Integration of Renewables: additional perspectives** **Co-chairs: Andreas Athienitis and Andrew Pape-Salmon**<br>**Marianne Armstrong**, Principal Research Officer, NRCC: *Resilience in building codes*<br>**Christian Bélanger,** Director Strategic and Transversal Projects, IREQ, Hydro-Québec: *Buildings and Electric power system of the future - A new partnership to define*<br>**Bryan Purcell**, Vice President of Policy and Programs, Atmospheric Fund & Federation of Canadian Municipalities: *Planning municipalities for sustainability and resilience*<br>**Sophie Hosatte – Ducassy,** Director- Buildings Group, CanmetENERGY, NRCan: *Building energy efficiency, advanced heat pumps, thermal storage and optimal control of high performance buildings* | | 14:30 – 15:30 |
| **ALL** | **CLOSING DISCUSSION** | 15:30 – 16:00 |

# INTEGRATION OF SMART BUILDINGS INTO THE ELECTRIC ENERGY GRID

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## ABSTRACT

This paper considers the present and future roles of the built environment towards attaining the ultimate objective of an energy system that is zero-carbon and resilient under extreme weather conditions or other disruptive events. Smart buildings in particular will be key players by becoming prosumers. This raises the policy challenge for Canada of how best to integrate them within the existing energy system so as to maximize their positive impacts.

## INTRODUCTION

The operator of an electric energy network must meet user demand while ensuring the stability of the electricity grid. This is particularly challenging during periods of peak demand because the system is then operating near its limits of both generation and transmission. This often requires bringing online the most expensive generating units, thus increasing the total cost of meeting demand.

At the same time, the electricity grid is aging and is thus more susceptible to weather events, human error, malicious attacks, and equipment failure. This increased susceptibility has led to an increase in the number and severity of utilities' operational problems. When these problems propagate in the power system they can lead to massive blackouts (NASME,2017).

Moreover, there is a global drive to integrate increasing quantities of renewable energy generation into the electricity grid. In Canada, solar and wind power capacity together represented 9% of the total power capacity in 2015 (NEB, 2016), and this proportion is expected to more than double by 2040 (NEB, 2017).

When large-scale renewable energy providers such as wind farms are connected to the grid, a further complication is added because of the fluctuating nature of this generation. These fluctuations require the network operator to keep in reserve, and to more frequently use, more of the most expensive generating units. Because these reserve units are almost always fuelled by natural gas, this leads to increased greenhouse gas emissions that cancel out some of the benefit from the integration of renewable energy.

This situation has created a great need for flexibility on the demand side of the electricity equation. In this paper we consider the opportunities for the smart buildings of the (near) future to provide such flexiblity, the risks involved, and the policy challenges that arise. While the discussion is framed in general terms, the relevance to the Canadian situation is highlighted throughout.

## SMART BUILDINGS AS THERMAL ENERGY STORAGE UNITS

We start from the perspective that a building can be viewed as a means to store heat. In other words, from the perspective of the grid operator, a building is able to store thermal energy by virtue of its use of electricity to operate heating/cooling devices. This includes not only space heaters and air conditioners but also appliances such as refrigerators, freezers, and hot water heaters. This means that buildings can provide flexibility to the grid to the extent that the operation of these devices can be shifted in time, and specifically out of peak demand periods and into periods of the day with lower demand.

The potential for flexibility provision by buildings in Canada is significant. Space heating is responsible for more than 60% of the total residential energy consumption (Stats Can 2013), and electric baseboards account for 27% of heating equipment nationally, and for 66% of it in Québec, a winter-peaking jurisdiction. Ontario is typically a summer-peaking jurisdiction due to the high penetration of air conditioning systems (OEB 2015, NRCan 2011).

Load shifting by users is generally referred to as demand-response (DR) or demand-side management (DSM). This is a well-known paradigm that has contributed to the operation of electric grids for many years. While DR programs have traditionally focused on taking advantage of the response capabilities of large industrial consumers, the advent of time-of-use pricing for electricity has partially tapped the DR potential of commercial and residential customers.

Smart buildings offer the prospect of maximum utlisation of the thermal storage potential of the built environment to provide DR services to the grid. From a practical perspective, individual buildings are unlikely to participate directly in providing DR because, differently from large industrial customers, their numbers are much larger and their DR capacities much smaller. The pooling and coordination of their capacities is done via a DR aggregator, or more generally, a virtual power plant. These are commercial entities that deploy their portfolio of commercial and residential DR providers to perform near real-time load shifting, and more generally to provide new ancillary services to the grid. (Ancillary services are all the functions required to maintain grid stability.) For example, customers in California can already choose to participate in such DR problems (CPUC, 2020).

In Canada, much of the leadership in this area has taken place in the Maritime provinces. The demonstration project *PowerShift Atlantic* (PowerShift Atlantic, 2015) aggregated around 17 MW of load from more than 1400 residential and commercial customers based on directly controlling their electric water heaters and electric heating. The *smartDESC* R&D project (Malandra et al, 2020) provided a proof of concept for the possibility to use a decentralized control architecture to provide DR. These projects demonstrated that commercial and residential DR is both technically possible and economically promising. Going beyond R&D, Saint John Energy is deploying a commercial energy management system to manage commercial and residential energy consumption at peak times (NRCan, 2019).

The provision of DR via the thermal storage capabilities of buildings is thus already becoming a reality in Canada, and is poised to grow in the future. In the rest of this paper, we glimpse into the future of the interaction of smart buildings with the electricity grid.

## SMART BUILDINGS AS PROSUMERS

The technological advances and decreasing costs of PV panels, batteries, and electric vehicles have led to an increasing integration of these technologies into the built environment. By taking the storage capacity of buildings and pairing it with these technologies, smart buildings become prosumers.

A *prosumer* both produces and consumes electricity and is hence able to manage its own electricity usage and supply. The advent of prosumers will be another major development in the current evolution of the electricity grid. Prosumers will directly contribute to the distributed integration of renewable energy in a pervasive manner, and hence will support the development of net-zero buildings and communities.

Prosumers have the potential to provide benefits to the grid as a whole through the provision of ancillary services. Furthermore, the distribution of generation throughout the grid may help to defer, or even avoid, the need for investment in new grid infrastructure to address congestion, reliability, or resilience issues. The value of their contribution will however depend on their attributes, including their location within the network and their availability when needed (NASEM, 2017).

The conditions for prosumers to blossom are becoming a reality. A recent study of residential prosumers in Europe reported that PV adoption is expected to reach 39.5% of the total potential residential solar PV capacity in Germany by 2030, 29.0% in Belgium, 26.4% in the Netherlands, 18.7% in Denmark, and even 13.1% in the UK (EC, 2017). This is without taking into account the synergies with battery storage, electric vehicles, and other prosumer technologies. In the Canadian context, Ontario and the Maritime provinces are promising jurisdictions for prosumers due to the combination of high penetration of renewables and relatively low hydro-electric generation, both of which lead to higher electricity prices thus making the economic case for prosumers more attractive.

The impact of prosumers on the grid will initially be difficult to detect within the total consumption of residential and commercial customers. However, there will be a critical threshold on prosumers penetration beyond which the ability of prosumers to adjust their consumption, possibly even by temporarily choosing operate in a stand-alone manner, will lead to increased uncertainty in load forecasting, and make it more expensive to maintain grid stability. We discuss this further in the next section.

An unexpected aspect of the nature of prosumers is that they have high expectations for acknowledgement of their contribution. A recent study in Finland that directly interacted with private solar panel owners and energy company representatives via interviews and observations concluded that prosumers are a new group of stakeholders in the grid who expect a relationship of reciprocity with the grid on the basis of co-production of energy (Olkkonen et al, 2017). This will clearly require adjustments on the part of many electricity providers.

## POLICY CHALLENGE FOR CANADA

The emergence of prosumers will follow one of two possible scenarios. In the first scenario, prosumers will focus on reducing their consumption from the grid, operating in a standalone mode (temporarily disconnected) or possibly even in disconnected mode (physically disconnected). The second scenario is that prosumers will remain connected and provide ancillary services, including flexibility, thus becoming active stakeholders of the electricity grid. These two scenarios are discussed in detail in Kuznetsova and Anjos (2019). We briefly summarize here the key points of their analysis and its implications for Canada.

One of the key motivators for grid disconnection is an electricity pricing structure that penalizes prosumers. For example, in Ontario in 2016 the cost of energy and power represented less than 9% of the typical electricity bill, with the remainder covering grid fees and various subsidies, environmental initiatives, fixed costs, and taxes (Kuznetsova and Anjos, 2019). Feed-in tariffs provided some compensation for this, but this economic incentive to remain connected has now been removed. By disconnecting from the grid, a prosumer could use the savings towards the setup equipment cost, and thus be protected from possible increases in the non-energy and power components of the electricity bill.

In Ontario, disconnection is particularly attractive for prosumers in low-density regions. Not only are their grid charges the highest in the province, but moreover they usually can more easily and cheaply accommodate the physical space needed for PV panels, storage, and other equipment required.

One of the consequences of the physical disconnection of large numbers of prosumers would be an increase in the economic pressure on the remaining connected customers who are faced with increased fees to maintain the network.

Furthermore, the economic viability of the electricity grid itself could be threatened. In Australia, the grid operators have been lobbying for compulsory connection fees in the residential and commercial sectors, regardless of whether the building in question is connected to the grid or not, or alternatively, for customers disconnecting from the grid to pay a penalty (Parkinson, 2015).

While it is in principle possible for all customers to become prosumers, if this were to happen, it would likely be in the form of local micro-grids within which participants can exchange energy according to availability and needs. This reflects in a smaller scale the main benefit of the electricity grid: the increased reliability provided by interconnections between buildings, communities, and provinces. The intent is that a microgrid should be able to function for more than a few minutes as a controlled electrical island (CIGRE, 2015).

It is therefore important to support and promote the rise of prosumers while proving incentives for them to remain connected to the grid. The objective should be to strike a satisfactory tradeoff between the interests of prosumers and the needs of the network operators.

One possibility is to encourage high levels of energy exchange between all stakeholders via the grid. This will require a large amount of investment in the grid infrastructure for it to be able to support *bi-directional flows of electricity*. This is because the current (local, low voltage) distribution systems are typically designed for the electricity to flow in only one direction, namely from the grid to the consumer. Significant modifications to existing distribution systems will be required to support the injection of electricity into the grid by prosumers while supporting the continuing use of existing infrastructure (CCA, 2015). A large-scale energy exchange mechanism would also be required, likely in the form of a market.

An alternative option is to encourage local energy generation and consumption within a micro-grid, as mentioned earlier, while keeping the connectivity to the electricity grid to be able to carry out a certain amount of energy exchange, and to benefit from the greater reliability of large-scale generation whenever the local energy balance is problematic due to seasonal, social, or other factors. This option would likely require less investment in infrastructure but would depend on having a suitable energy pricing structure that is attractive for both local communities of prosumers and the grid operator.

One proposal to reconcile their interests is *time-and-level-of-use pricing (TLOU)* (Gómez-Herrera and Anjos, 2018, 2019). This is an extension of the time-of-use (TOU) pricing that is widely used, for example in Ontario. TLOU extends TOU by having the electricity price vary not only according to the time of day but also according to the total amount of power used at the same time. The idea is that the customer (prosumer, micro-grid) and the grid agree in advance on a maximum power capacity for each period of the day, for example every hour. TLOU then charges a lower price for the energy consumed up to the power capacity limit, and a higher price for energy exceeding the limit. The original motivation for TLOU is to encourage consumers to even out their consumption throughout the day, but it equally benefits prosumers who can negotiate the individual power capacity limits, and hence the cost of energy from the grid, according to their capabilities and needs.

In closing, it is important to remember that the successful nurturing and integration of prosumers into the Canadian electricity grid will support the integration of renewable generation in the energy system, and hence reduce the use of fossil fuels in meeting Canada's energy needs.

## CONCLUSION

This paper provided an overview of the present and future roles of the built environment in an electricity grid with increasing integration of renewables, with the ultimate objective of achieving an energy system that is zero-carbon and resilient under extreme weather conditions or other disruptive events. Smart buildings in particular will become key players with the advent of prosumers. This raises the policy challenge for Canada of how best to integrate them within the existing energy system so as to maximize their positive impacts. Key policy issues to incentivize prosumers to remain grid-connected include:

- Acknowledging the role of prosumers within the electricity system as co-producers of energy.
- Supporting local energy management within grid-connected micro-grids via suitable pricing schemes.
- Establishing a large-scale energy exchange mechanism.

The Montreal symposium will be a welcome opportunity to discuss these issues and propose ways to address them in the Canadian context.

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# DESIGN AND OPERATION OF RESILIENT AND FLEXIBLE BUILDINGS

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## ABSTRACT

This paper reviews some of the key technological developments that led to modern buildings – their building envelopes and their heating and cooling systems and the more recent energy generating systems from renewable on-site energy sources. Current challenges to achieve energy resilience to extreme weather events and other disasters are discussed. Flexibility in building design to facilitate adaptation to evolving needs and operational flexibility in the interaction with smart grids are discussed. Efficient integration of HVAC and building-integrated solar technologies, along with energy storage are discussed as a means of achieving energy resilience, including designing buildings to resist the spread of viruses such as COVID19.

## INTRODUCTION

Buildings have evolved over the centuries from the traditional mud-brick and stone structures, or timber houses, into the complex structures that define our built environment today[1]. To provide structural strength we now typically design steel structures, concrete structures or wood structures or increasingly hybrid structures. The building envelope that separates the indoor from the outdoor environment consists of two main parts – an opaque part and the fenestration; the opaque envelope typically includes several layers that have different functions – the inner layer hides many of the services (e.g. wiring and piping) but also has a protective function from moisture exfiltration in the indoor environment. Insulation is typically placed between and behind structural members and then there are the outer layers that have traditionally been passive and have a weather barrier /weather protection function.

The fenestration has evolved from single glazing[2] to the sealed double glazed units (with air in the cavity) that became widespread in the last decades of the 20th Century. A major advance in fenestration was the adoption of a low-emissivity coating on one of the two surfaces in the cavity that reduces radiation heat transfer between the two surfaces by about 90%; the convection heat transfer between the two surfaces is also reduced by about 20-40% by using inert gases such as Argon and Krypton in double-glazed units and further through insulated framing systems. In colder climates, triple-glazed units also started becoming common. The adoption of low-e windows started becoming widespread in North America during the period 2005-2010, although low emissivity coatings were developed since the 1980's (Rissman and Kennan, 2013). This adoption of low-e windows enabled designers to adopt increasingly larger window areas so as to have more daylight and better views to the outdoors, but heating and cooling loads started to rise as a result of this new trend.

## BUILDINGS AND ADOPTION OF HVAC & ENERGY SYSTEMS

In much of the world, buildings until the beginning of the 20th century were **passive structures** with manually operable windows, relying on natural ventilation for cooling and combustion of fossil fuels for space heating.

A major development in the modern industrial era was the adoption of **electricity** with the development of alternating current motors that made possible the invention of oscillating fans in the early 20th century and artificial lighting with incandescent lamps. In the early 20th century, Willis Carrier invented the first modern **air-conditioning** (AC) system; its initial purpose was dehumidification. In 1922, Carrier invented the centrifugal chiller, which added a central compressor to reduce the unit's size. The widespread adoption of AC units in US homes took about 40-50 years. By the late 1960s, most new homes had AC, fueling population growth in hot-weather states like Florida. AC is now in 87% of all US households[3]. In Canada, the adoption of AC was slower in homes until **heat pumps** became widely available at a relatively low cost, with the capability to do both heating and cooling. The rate of adoption of heat pumps is increasing and this trend will

[1] https://www.buildingscience.com/documents/digests/bsd-007-historical-development-of-the-building-enclosure

[2] The Romans were the first known to use glass for windows, a technology likely first produced in Roman Egypt, in Alexandria ca. 100 AD (Wikepedia) but it started being widely used only in the 17th Century in England.

[3] https://www.energy.gov/articles/history-air-conditioning

continue with higher efficiency modulating units available at lower cost.

**Solar technologies** – mainly solar thermal and photovoltaic (PV) panels have been developed in the last 60-70 years. Solar thermal collectors are mainly used for water heating and, while PV produces electricity, PV/thermal collectors have also started being developed in the last 20 years to produce both electricity and heat. Standalone PV is the lowest cost electricity resource in the world at roughly \$0.65/watt[4], but is limited by intermittency, associated grid issues, institutional barriers, lack of market capacity and other major barriers to integration in buildings and public spaces. Steps are being taken around the world on the production of Building-integrated photovoltaics (BIPV) and more recently BIPV/thermal systems (BIPV/T). With BIPV/T systems, the building skin becomes essentially a solar collector that produces electricity and useful heat.

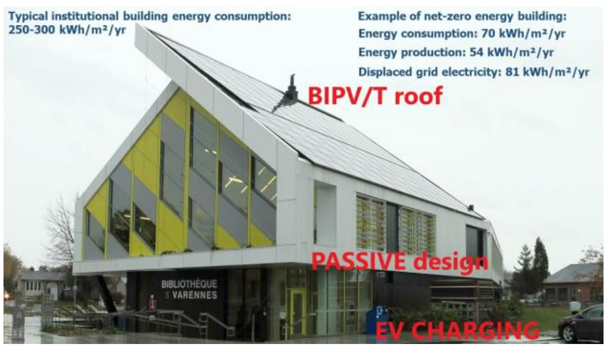


***Figure 1.*** *Varennes Library – Canada's first institutional NZEB with a building integrated photovoltaic/thermal system, passive solar design, EV charging, a geothermal heat pump system and radiant slabs.*

## NET ZERO ENERGY BUILDINGS

The feasibility of new **net-zero energy buildings** (NZEBs) that integrate ultra-high energy efficiency with on-site renewable energy generation to produce, in an average year, as much energy as they use, has been recently demonstrated both for detached houses and low- to mid-rise commercial and institutional buildings, both in Canada and other developed countries (Athienitis and O'Brien, 2015). Many definitions exist for NZEBs, most recently documented and discussed under IEA SHC Task 40 / EBC Annex 52 (Voss, 2011) and new integrated design approaches are being developed. NZEBs need energy storage to achieve energy resilience in the event of power outages and also to provide flexibility to smart grids. This storage could be thermal or battery (or both) and an EV/PHEV could possibly be used to trade energy with a smart grid and provide backup power. In Canada, the first institutional solar NZEB, the Varennes Library, was inaugurated in 2016 (Dermardiros et al., 2019). A similar archetype building could be designed to generate twice as much electricity and heat, possibly powering and heating adjacent buildings and providing resilience through adequate energy storage and micro-grids.

Design of buildings and groups of buildings (communities, clusters) for resilience creates new challenges. A major challenge is setting the **goals for energy resilience**: **for how long should a community be able to generate its own power and heat** in natural disasters such as Ice-storm 98 (Lecomte, 1999) that resulted in up to 5-week power cut, 4.7 million people displaced in Québec and Ontario and economic loss of over \$6 billion. This led to significant damage to buildings after their occupants evacuated them due to utility outages, resulting in extensive water damage from frozen water pipes and contributing to the economic loss. Such damage could be greatly reduced through resilient solutions that enable on-site electricity and heat production with building-integrated renewables.

A simulation study (Bambara et al., 2020) was conducted to evaluate the impact of replacing aging detached houses in Montreal with two houses of equivalent living areas on the same land lot. The new high efficiency houses can reduce energy consumption by 67% (22,600 versus 7,300 kWh/year) and a photovoltaic roof can generate nearly 3 times more energy than the house consumes (43,300 kWh/year). In addition to the advantage of doubling the number of inhabitants on the same land area, densification has the potential to transform the current status of people consuming 5,640 kWh/year to becoming net producers of 3,580 kWh/year. The excess solar electricity generated by the new houses could be instrumental in decarbonizing the transportation sector by providing clean power for electric vehicles, which in-turn can provide bi-directional energy flow from/to buildings as needed.

## BUILDING ENVELOPE, DURABILITY

The building envelope is critical in achieving high performance resilient and flexible buildings. Its performance directly affects the energy efficiency, indoor environmental quality, and durability. The role of building envelope has evolved from a conventional environmental separator to an important element in moderating indoor environment and contributing to the energy generation and resilience. Energy efficiency and durability of the building envelope are two cornerstones of sustainable building design. Building envelope is intended to have a long service life and is costly to maintain and repair if failures occur. The **durability of the building envelope** is influenced by the combination of the environmental loads, namely, temperature,

[4] https://iea-pvps.org/wp-content/uploads/2020/01/2019-223_RP-ANU_DER-PVNORD_CBaldus-Jeursen_YPoissant_EN.pdf

moisture and UV radiation. The presence of moisture is a key element associated with most degradation mechanisms. In areas with higher amount of wind-driven rain, rain penetration is the main source of moisture, such as Southern British Columbia. The systematic building envelope failure due to rain penetration cost $2 billion for repairs (Barrett, 2000). For cold climate, moisture due to air leakage and vapour diffusion are the main sources. There are numerous cases of failure of building envelopes, often due to a mis-understanding of the environmental loads and the performance of these building envelope systems to specific microclimates (Lstiburek, 2006). Unless properly designed, particularly during retrofits, highly insulated building envelope may have reduced drying capacity and increased risks for moisture damage.

The mean global temperature has increased by 0.85°C compared to the pre-industrial period (1850-1900). For Canada, the temperature rise was double and in the arctic latitudes the increase was triple (Pachauri et al., 2014). Higher precipitation totals have been projected for all parts of Canada with the highest increases projected for the northernmost regions. For certain locations, it is projected that increases in the frequency, intensity and duration of precipitation as well as increase in peak wind loads and the frequency of occurrence of extreme winds (Lacasse et al., 2020) with associated wind driven rain.

Buildings built today are optimized based on historical climatic conditions. With a warming climate, more frequent extreme weather events are anticipated and these buildings will be exposed to a climate that is significantly different than that observed historically during their service life. Therefore, they need to be able to adapt to future climatic conditions, as well as to function as intended during extreme weather events such as heat waves, ice storms and wind stroms with heavy rain. Under the projected future climates, the heating energy demand would be reduced, while the cooling energy demand would significantly increase. The overheating risk during summertime would be signficantly increased in the future (Baba and Ge, 2019). Therefore, buildings typically designed to reduce heating energy consumption need to be optimized based on projected future climates. Buildings also need to be able to maintain acceptable indoor thermal conditions during **extreme weather events** such as heat waves or ice storms with low requirement of power. The integration of renewables such as photovoltaics (BIPV, BIPV/T, semi-transparent PV windows) can serve the conventional building envelope function as well as generating electricity and thermal energy. To function as a Building Envelope system, it needs to fulfill the function of controlling heat, air and moisture, fire, noise transmission, and provide structural resistance to earthquakes and wind. The electricity generated from BIPV systems may provide energy needed during these extreme weather events and power outage. Currently there is no standard for evaluating the performance of BIPV and BIPV/T as building envelope systems and this is a major barrier to their adoption. Inclusion of BIPV in building codes is also an urgent need.

## HYBRID AND NATURAL VENTILATION

The **COVID19 pandemic** has further revealed the need for buildings and their ventilation systems to be designed to limit the spread of pathogens, such as COVID19, which has been shown to be spread as aerosols (Li et al., 2020). This can be done by reducing recirculation of HVAC air and bringing in more fresh air to dilute pathogen concentration, thus limiting the spread of infections (ASHRAE, 2020), in addition to use of special filters and UV disinfection measures. Canadian buildings need to be able to face crises such as ice-storms and pandemics simultaneously since **both typically happen in winter**; if they do, physically distancing with millions of people displaced from their homes and relocated in confined places/shelters will be very difficult, if not impossible, possibly resulting in many more deaths than what we experience with the COVID19 pandemic, currently in its second wave.

Natural ventilation (NV), is the process of replacing stale or noxious indoor air with fresh air without using mechanical means. NV was used since ancient times; for example, Persians and Egyptians used curved-roof vents to control the level of indoor dust so as to reduce the risk of getting respiratory diseases by enhancing ventilation (Allard and Santamouris, 1998). NV is also widely applied in both residential and commercial buildings to reduce indoor $CO_2$ concentrations (Stabile et al., 2017), lower the risk of sick building syndrome (Seppänen and Fisk, 2002), provide acceptable thermal comfort, and achieve energy savings when the quality of the outdoor air is suitable for NV. It was reported that by replacing the mechanical ventilation system with a NV system, annual energy consumption was reduced by 18-33% while maintaining acceptable classroom comfort levels (Gil-Baez et al., 2017). According to opening locations, there exist two main types of NV: single-sided ventilation and cross-ventilation. In single-sided ventilation, only one façade is designed to have openings, whereas cross-ventilation is enabled by two or more openings on adjacent or opposite façades.

NV is well suited to Canadian climates that are characterized by long seasons of cool-mild outdoor environments from May to October (ECCC, 2014). Figure 2 shows the maximum annual total NV potential hours for a 70 W/m$^2$ cooling load across North America with the arrows indicating the best window-facing directions. For example, the study showed that Toronto has a NV potential of 1,600 hours/year of southwest facing single-sided NV compared to the 1,500 hours/year with northeast-facing windows in Vancouver. The difference is because Toronto has a higher average daily temperature and more suitable for the rated cooling load of 70 W/m$^2$ (Cheng et al., 2018)

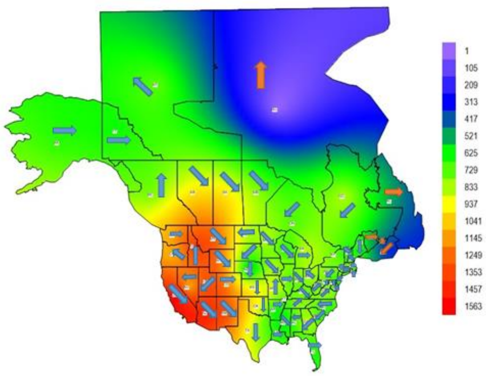


***Figure 2**. Natural ventilation potential in North America.*

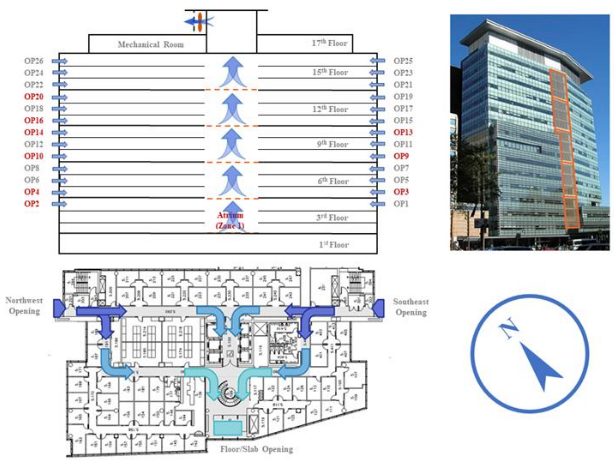


***Figure 3**. An institutional high-rise building with HV.*

When NV alone cannot satisfy the needs of air exchange or space cooling, mechanical fans and artificial cooling are added, so hybrid ventilation (HV) applies. Previous studies found that HV could save 90% of cooling system energy when proper control strategies were in place (Ezzdeldin and Rees, 2013). The study applied hybrid ventilation to space cooling in a desert area with diurnal temperature variation. A climate-responsive operation strategy was designed that incorporated several technologies (i.e., direct evaporative cooling, borehole heat exchanger, night convective cooling strategy, and radiant cooling elements coupled to a cooling tower). HV was found to contribute to more than 40% of the total energy savings while at the same time providing satisfactory thermal comfort. A higher temperature set point with a higher thermal mass used in the design reduced temperature fluctuations and improved thermal comfort in the building. A whole-building study that integrated HV and building thermal mass was conducted in an institutional high-rise building (Yuan et al., 2018) (Figure 3) at Concordia University; it showed that 180 Whr/m$^2$ of cooling energy could be saved in the daytime after the corridor concrete floors had been chilled by HV for four hours during the night. Nagano et al. (2006) applied a phase-change material (PCM) to the floor in a air-PCM ventilation system and showed that the PCM increased the thermal storage to 1.79 MJ/m$^2$. Zhang (2019) studied the building in Figure 3 with the integrated HV and PCM systems and found that the PCMs could double the stored heat.

The design and operation of NV and HV systems for resilient and flexible buildings need to address the following major challenges:

- The design of a NV/HV system must be based on a systematic and integrated approach, starting at the conceptual design stage due to many interacting parameters involved: outdoor and indoor conditions, many building parameters (site, shape, orientation, window-to-wall ratio, internal layouts), thermal comfort and ventilation requirements. Many major decisions have to be made at the initial stage as the modification of an existing system is difficult and more expensive.
- The NV/HV system design must also address important issues such as fire protection, because the same system, which is designed for energy saving, may facilitate a quicker fire smoke spread during a fire, and thus may create a fire risk. A typical NV/HV system must be designed to accommodate both fire-protection and non-fire-protection modes, such as through automatic fire-proofing dampers aided by advanced sensor systems for fire smoke zoning and separations. The NV/HV system must also be controlled as a function of the variable ambient weather and air quality through sensor systems both indoors and outdoors. It should also adaptively increase the amounts of fresh air (possibly solar heated) **to remove viruses such as COVID19** while recovering energy from the exhaust air.
- For regions with significant diurnal temperature variations, there often exists a mismatch between demand and response for a NV/HV system. The peak cooling load may occur in the middle of the day, whereas the outdoor temperatures are unsuitable for NV/HV; when the outdoor air temperature is low at night, the indoor cooling load may become so low that natural ventilation becomes unnecessary. This problem can be solved by the use of load-shifting techniques. The thermal mass can be cooled at night so that it cools down the indoor environment during the daytime. The thermal mass also helps to stabilize the variation of indoor temperature for better thermal comfort when the outdoor temperature fluctuates. The operation of a NV/HV system should be in a proactive manner. It can be based on model-predictive controls with future weather forecasts as inputs, so that the system reacts early enough before an extreme weather event occurs or when there is a foreseeable need for flexible building operations.

## CONCLUSION

This paper considered the historical evolution of buildings to controlled indoor environments protected by a resilient and durable building envelope that can now integrate renewable energy sources. It is now possible for buildings to generate as much energy from renewable sources as they consume while supporting smart grids, and even to generate electricity for electric vehicles, thus further contributing to reducing GHG emissions. As the current COVID19 crisis shows, it is increasingly important to design resilient buildings that also have flexible ventilation systems that eliminate contaminants and viruses. The CAE Roadmap will need to address the challenges of resilience, decarbonization and a healthy indoor environment in an integrated manner.

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# NET-ZERO READY BUILDING CODES

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## ABSTRACT

This paper provides an overview of current legislation and regulatory frameworks or proposals of three levels of government to achieve "net-zero energy ready" new construction over the next decade. The paper defines the performance standard, highlights policy drivers, and compares and contrasts the approach of three levels of government from the perspectives of technical performance of buildings, consistency, compliance and enforcement, and opportunities for transformative market change. While the scope of the paper is limited to current building code objectives, namely energy efficiency, it provides a foundation for future research on decarbonization and resiliency of buildings.

## INTRODUCTION

This paper provides an overview of current legislation and regulatory frameworks or proposals of three levels of government to achieve "net-zero energy ready" new construction over the next decade. The three levels of government include the federal government publishing of the National Building Code of Canada (NBC), the Province of BC's Energy Step Code within the BC Building Code (BCBC) and the City of Vancouver's Building Bylaw and rezoning policy.

Codes Canada publishes the NBC and the National Energy Code for Buildings (NECB) approximately every five years, with the 2020 edition anticipated by the end of 2021. While the federal government publishes the NBC, it is the provinces, territories and charter cities such as Vancouver that adopt it in regulation, along with its various performance standards.

A key federal policy driver is the Pan Canadian Framework on Clean Growth and Climate Change. It states, "The Government of Canada will work with the provinces and territories to … develop a "net-zero energy ready" model building code, with the goal that provinces and territories adopt it by 2030" [ECCC 2016]. This precipitated amendments to the NBC and NECB that were posted for public review in early 2020.

The BCBC is adopted in regulation under the *Building Act*, applying to owners and developers of buildings. The *Local Government Act* and *Community Charter* enable local governments to implement the BCBC and enforce it through local government bylaws and building permits. Local governments are unable to enforce technical standards that are "matters" referenced in the BCBC unless the Building Act General Regulation [Queen Printer 2020-1] explicitly makes a matter "unrestricted" such as the form, exterior design, or finish of buildings relating to wildfire hazard (a topic of resiliency). In the case of the conservation of energy and the resultant reduction of greenhouse gas emissions, a local government can reference any step of the BC Energy Step Code in policy or bylaw.

A key policy driver is the 2018 CleanBC Plan that includes a commitment to "Improve the BC Building Code in phases leading up to 'net-zero energy ready' by 2032". This includes making homes and buildings 20 per cent more energy efficient by 2022, 40 per cent more energy efficient by 2027, and 80 per cent more energy efficient by 2032 – the net-zero energy ready standard" [BCECCS 2018].

The BCBC objectives include "Energy Efficiency and Water Use" to "limit the probability that, as a result of the design, construction or renovation of the building, the use of energy will be inefficient or the use of water will be excessive." [Queens Printer 2020-2]. Energy security, carbon intensity and resiliency are beyond the scope of this paper, but conclusions are drawn to inform future research on those topics.

The regulatory jurisdiction of the City of Vancouver is governed by the *Vancouver Charter*, and that includes authority to publish its own building bylaw with unique technical standards, including regulations for the reductions of greenhouse gas emissions [Queens Printer 2020-3]. In practice, the Vancouver Building Bylaw standards are harmonized with the BCBC, but in some areas adopt different standards. Vancouver's "rezoning policy" has very stringent energy efficiency and emission management standards which is only triggered when changes in density, height or use is sought.

**Definition of Net-Zero Energy Ready**

There are several definitions on 'Net-Zero Energy' (NZE) vs. 'Net-Zero Energy Ready' (NZER) buildings/houses. The following established definitions are frequently referenced:

- The Canada Mortgage and Housing Corporation [CMHC 2018] defines a NZE house as:

*A house that is designed and built to reduce household energy needs to a minimum and includes on-site renewable energy systems, so that the house may produce as much energy as it consumes on a yearly basis.*

- Natural Resources Canada [NRCan 2020] defines:

*A Net-Zero Energy (NZE) house is a house that produces as much energy from on-site renewable energy sources as it consumes each year, and*

*A Net-Zero Energy Ready (NZER) house is a variant of the NZE house in which the builders have not installed the renewable energy generation system.*

- BC Energy Step Council [ESC 2020] defines:

*Net-zero energy buildings produce as much clean energy as they consume. They are up to 80 percent more energy efficient than a typical new building, and use on-site (or near-site) renewable energy systems to produce the remaining energy they need, and*

*A net-zero energy ready building is one that has been designed and built to a level of performance such that it could, with the addition of solar panels or other renewable energy technologies, achieve net-zero energy performance.*

## DISCUSSION AND RESULT ANALYSIS

The current and proposed codes and standards to achieve net-zero energy ready construction are highlighted below.

**BC Energy Step Code**

The BC Energy Step Code (ESC) was included as an optional compliance path into the BC Building Code (BCBC) in April 2017. The fourth and most recent amendment was included in the BCBC 2018 mid-cycle revision that took effect on December 12, 2019 [MAH 2019]. The BC ESC provides a technical "roadmap" to net-zero energy ready construction. It includes between three and five tiers for the following building types in all climate zones within the province:

- Part 9 residential;
- Part 3 hotels and motels;
- Part 3 residential;
- Part 3 office; and,
- Part 3 business and personal services or mercantile.

The tiers have increasingly stringent energy efficiency requirements for whole-building or mechanical end-use intensity, building envelope thermal performance, and in some cases airtightness. The BC ESC does not include prescriptive solutions; rather is exclusively a performance-based code. All buildings are required to undertake energy modelling and conduct a whole building airtightness test.

Tier 1 is always equivalent to the performance of the BCBC Division B acceptable solutions set out in section 9.36 or section 10.2. The BCBC s9.36 is based substantially on the NBC 2015 and s10.2 references both ASHRAE 90.1 2016 and NECB 2015 as acceptable solutions. The BC ESC energy modelling is primarily based on the performance paths of BCBC/NBC s.9.36.5 or NECB 2015 Part 8. It also references the City of Vancouver Energy Modelling Guidelines.

The most recent amendment to the BC ESC included a first tier (with no performance requirements) for Part 3 public sector archetypes, including schools, libraries, colleges, recreation centres, hospitals and care centres, effectively requiring energy modelling and air tightness testing for those buildings [MAH 2019].

The BC ESC top tier is designed to be equivalent to "net-zero energy ready" construction. For houses, Step 5 requires a mechanical end-use intensity (MEUI) as low as 25 kWh/m$^2$/yr, excluding plug load and lighting, a thermal energy demand intensity (TEDI) of 15 kWh/m$^2$/yr, and an airtightness of 1 air change per hour at 50Pa pressure differential ($ACH_{50}$). Passive House certified houses are deemed compliant with Step 5. An alternative Step 5 compliance path for TEDI includes a 50% improvement compared to an EnerGuide Rating system reference house. Alternative compliance paths for both TEDI and MEUI apply to Steps 2 through 4 based on EnerGuide; up to 40% for MEUI and 20% for TEDI, aligned with the NBC 2020. MEUI for all steps depend on climate zone, size of house, and use of cooling energy. TEDI requirements can be adjusted to reflect the specific heating degree days in the community where the house is located.

For multi-family residential buildings, Step 4 is the highest tier, with total energy use intensity (TEUI) as low as 100 kWh/m$^2$/yr in Climate Zone 4, including plug load and lighting, and a TEDI of 15 kWh/m$^2$/yr. These figures increase to TEUI $\leq$ 140 and TEDI $\leq$ 60 in Climate Zone 8.

For hotels and motels Step 4 is the highest tier, with TEUI as low as 120 kWh/m$^2$/yr and TEDI $\leq$ 15 in Climate Zone 4.

For other Part 3 buildings, the top tier is Step 3, with TEUI as low as 100 kWh/m$^2$/yr and TEDI $\leq$ 20 in Climate Zone 4 for offices, and TEUI as low as 120 for business and personal service and mercantile occupancies with TEDI ≤ 20.

**National Building Code 2020**

Codes Canada conducted the final public review of the next edition of the national codes from January to March 2020. Two proposed tiered performance requirements were introduced: one for the NBC Section 9.36. (Part 9 Residential Buildings) and one for the NECB (Part 3 Buildings). The tiers represent voluntary standards that have been codified. This provides increased flexibility to authorities having jurisdiction (AHJ). It is up to the AHJ to decide whether to adopt a tier or not, and at which level. The publication of these voluntary tiers in the code should help industry and the public prepare for potential upcoming code changes, essentially 'priming' the market for upcoming code cycles.

**Tiered Performance (NBC Section 9.36.)**

The Proposed Code Change Form (PCF) 1617 [Codes Canada 2020-1] introduces a new Subsection that establishes tiered performance requirements by defining five tiers in terms of overall energy performance improvement, improvement in building envelope performance, and airtightness level. The tiers are based on a reference case of the 2015 NBC and represent percentage improvements in energy performance of 10%, 20%, 40% and 70% for Tiers 2 through 5 respectively. For the envelope, the improvements are 5%, 10%, 20% and 50% compared to the reference case.

For airtightness, there are two target levels, albeit the PCF 1610 [Codes Canada 2020-2] includes 6 possible levels that span from 3 air changes per hour (at 50Pa) to 0.6 $ACH_{50}$. Two additional airtightness methodologies using the Normalized Leakage Area (NLA) or the Normalized Leakage Rate (NLR) approach are included – the NLA@10 and the NLR@50.

To supplement this tiered approach, it adds a new Subsection on prescriptive requirements for compliance with Tier 2 above (i.e., 10% improvement compared to reference case, 5% improvement in building envelope, level 1 airtightness) based on a points system that links to dozens of performance improvement technologies and designs. This is documented in PCF 1611 [Codes Canada 2020-3].

**Tiered Performance Requirements (NECB)**

Similar tiered performance requirements were introduced for the NECB through PCF 1527 [Codes Canada 2020-4].

As Tier 1 requirements are the same as the balance of the NECB there is no cost impact or energy savings attributed to this Tier.

***Table 1.*** *NBC 2020 Tiered Performance.*

| Tier | Performance vs. Target | % Improvement of Envelope | Airtightness Level [1] |
|---|---|---|---|
| 1 | ≥0% | n/a | Test only |
| 2 | ≥10% | ≥5% | 1 |
| 3 | ≥20% | ≥10% | 1 |
| 4 | ≥40% | ≥20% | 3 |
| 5 | ≥70% | ≥50% | 3 |

Note (1): Airtightness Levels are defined in Table 3.

***Table 2.*** *NBC 2020 Airtightness.*

| Airtightness Level | $ACH_{50}$ | $NLA_{10}$ | | $NLR_{50}$ | |
|---|---|---|---|---|---|
| | | $cm^2$ | $in^2/100\,ft^2$ | $L/s/m^2$ | $cfm_{50}/ft^2$ |
| 1 | 3.0 | 1.92 | 2.76 | 1.17 | 0.23 |
| 2 | 2.5 | 1.60 | 2.3 | 0.98 | 0.19 |
| 3 | 2.0 | 1.28 | 1.84 | 0.78 | 0.15 |
| 4 | 1.5 | 0.96 | 1.38 | 0.59 | 0.12 |
| 5 | 1.0 | 0.64 | 0.92 | 0.39 | 0.077 |
| 6 | 0.6 | 0.38 | 0.55 | 0.23 | 0.046 |

***Table 3.*** *NECB 2020 Tiered Performance.*

| Energy Performance Tier | Performance of Proposed Building Relative to Performance of Reference Building (% building energy target) |
|---|---|
| 1 | ≤ 100% |
| 2 | ≤ 75% |
| 3 | ≤ 50% |
| 4 | ≤ 40% |

Progressive Tiers were selected to improve efficiency levels, leading to a fourth tier which is equivalent to net zero energy ready performance. Based on Codes Canada committee work Tier 4 was originally set at 25% of the reference building energy target, or a 75% reduction in energy use, the modelling rules, non-regulated loads, and fixed loads, made this target near impossible to achieve for several building typologies [Personal communications between author and committee]. As a result, the Tier was increased to 40%, for the proposed NECB-2020, to enable progressive designs to achieve Tier 4 irrespective of building type.

The four tiers for the NECB are shown in Table 3.

**Vancouver Building Bylaw (VBBL)**

In July 2016, Vancouver City Council approved the Zero Emissions Building Plan, aimed at reducing emissions from new buildings by 90% in 2025 [Vancouver 2016]. The Plan also adopted a target of reducing emissions from all newly permitted building to zero by 2030. To achieve this, the City is setting limits on emissions and energy use in new buildings through several policy levers. As noted earlier, the Vancouver Building Bylaw closely matches the BC Building Code, with the exception of significantly more stringent standards for one- and two-family houses, not documented in this paper.

The Green Building Policy for Rezonings applies when a development falls outside of the “Community Plan” for the particular neighborhood with respect to height, density, occupancy and other factors. This represents a sizable proportion of construction activity in the city [Personal communication with City of Vancouver]. It includes two alternative compliance paths based on the carbon intensity of the fuels used for the building. Table 4 illustrates that energy efficiency requirements are less stringent for buildings with lower carbon fuels, resulting in an equivalent greenhouse gas intensity (GHGI) under both compliance paths.

***Table 4.*** *VBBL Rezoning Requirements.*

| Performance Limits<br>Buildings Not Connected to a City-recognized Low Carbon Energy System | | | |
|---|---|---|---|
| Building Type | TEUI ($kWh/m^2$) | TEDI ($kWh/m^2$) | GHGI ($kgCO_2/m^2$) |
| Residential Low-Rise (< 7 storeys) | 100 | 15 | 5 |
| Residential High-Rise (7+ storeys) | 120 | 30 | 6 |
| Office | 100 | 27 | 3 |
| Retail | 170 | 21 | 3 |
| Hotel | 170 | 25 | 8 |
| All Other Buildings | EUI 35% better than Building By-law energy efficiency requirements, Section 10.2, in effect at the time of rezoning application | | |

| Performance Limits<br>Buildings Connected to a City-recognized Low Carbon Energy System | | | |
|---|---|---|---|
| Building Type | TEUI ($kWh/m^2$) | TEDI ($kWh/m^2$) | GHGI ($kgCO_2/m^2$) |
| Residential Low-Rise (< 7 storeys) | 110 | 25 | 5 |
| Residential High-Rise (7+ storeys) | 130 | 40 | 6 |
| Office | 110 | 27 | 3 |
| Retail | 170 | 21 | 3 |
| Hotel | 170 | 25 | 8 |
| All Other Buildings | EUI 35% better than Building By-law energy efficiency requirements, Section 10.2, in effect at the time of rezoning application | | |

TEUI: Total Energy Use Intensity
TEDI: Thermal Energy Demand Intensity
GHGI: Greenhouse Gas Intensity

### Comparison and Analysis

The following highlight the differences between the four profiled “net-zero energy ready” codes – the BC Energy Step Code (BC ESC), the proposed National Building Code (NBC) 2020, National Energy Code for Buildings (NECB) 2020, and the City of Vancouver Green Buildings Policy for Re-zoning (COV).

All four codes include a performance path, leaving it to the developer/builder to ensure the building meets targeted performance outcomes. Up to four specific performance outcomes are required: (i) airtightness; (ii) energy use intensity (EUI), (iii) thermal energy demand intensity (TEDI), and (iv) greenhouse gas intensity (GHGI). Only the first requirement is measured, whereas the remaining three are modelled. The modelled values can be later verified through measured energy consumption and sub-metering; however, this falls outside of the timeframe that a building permit applies.

The primary driver for the BC ESC, NBC and NECB is energy efficiency. Up to three energy performance indicators are included – whole-building, building-envelope and airtightness. The NECB does not include TEDI. By having airtightness, TEDI, and/or a percentage envelope improvement to the reference building, the codes adopt an “building envelope first” framework, which prevents a designer from meeting the whole-building efficiency with mechanical solutions alone.

The COV drivers include both energy efficiency and greenhouse gas reductions, adding a limit to modelled emissions from the building, both direct from the combustion of fuels and indirect from the production of electricity. However, the approach allows for reduced energy efficiency for lower carbon fuels. This is misaligned with economic optimization given that low-carbon fuels are often higher cost to consumers and therefore there is rationale for increased levels of energy efficiency. This could compromise consumer affordability due to both lower energy efficiency and higher cost fuels. It would be appropriate to retain the TEDI between the two fuel choices for resiential, as Vancouver has done for office, retail and hotel (albeit not for residential), thereby reducing heat loss and protecting affordability.

Based on the author’s experience the performance tiers of the BC ESC and COV are based on best practices of previously constructed buildings within generalized archetypes that represent a large proportion of construction. The reference case is based on a fixed EUI, TEDI and (for Part 9 Buildings only) airtightness level. In contrast the NBC and NECB are based on the building-specific reference case, a hypothetical building that aligns with the design and meets the prescriptive requirements of NBC and NECB. In all four codes, the design must have an energy performance that is better than the reference building.

In three of the codes (excluding COV), the lower tiers are aligned with financially optimized design solutions with a positive net-present value (NPV) of energy bill reductions versus incremental capital costs based on [BC Housing 2018]. The upper tiers are based on technical best practices and best-available technologies, which in some cases have a positive NPV and in other cases are not strictly "cost-effective", depending on the architectural design of the building. However, the financial assessment overlooks the fact that current carbon pricing is unlikely to address the necessary costs to mitigate emissions, and henceforther market failures exist, a topic for future research.

With their fixed reference cases, the BC ESC and COV approaches allow for greater consistency, verifiability and enforcement. In contrast, the NBC and NECB with hypothetical reference cases can vary for each individual designer and energy modeller, thereby reducing consistency across the marketplace. The local autorities having jurisdiction will be unlikely able to verify the reference case due to the complexity of modelling. Several BC urban municipalities have concerns with the reference case for thermal performance in lieu of TEDI, suggesting this will undermine the "building envelope first" design approach. Absent a formal evaluation, measurement and verification system with calibrated energy modelling, it will be difficult to identify the differences between designers. Furthermore, the BC ESC and COV use energy modelling guidelines to enhance consistency, and the Engineers and Geoscientists of BC and Architectural Institute of BC have published professional practice guidelines for energy modelling services.

There are some differences in the number of tiers and their stringency, depending on the particular code. For Part 9 Buildings, both the BC ESC and NBC have the same number of steps and similar expectations of performance improvements of 10%, 20%, 40% and 50+% based on BC Housing [2018]. However, the airtightness requirements for the equivalent tier of the NBC are less stringent. For example, the Step/Tier 3 airtightness is 3ACH50 and 2.5ACH50 for NBC and BC ESC respectively. For Step/Tier 5, those compare at 2ACH50 and 1ACH50.

For Part 3 buildings, the BC ESC and NECB have the same number of steps, but slightly different expectations of performance improvements based on BC Housing [2018]. BC ESC steps 2, 3 and 4 are estimated to achieve improvements up to 40%, 50% and 60% [BC Housing 2018]. The percentage improvements in NECB-2020 are 25%, 50%, and 60% for tiers 2,3,4 respectively, as compared the prescriptive standards in NECB. To allow for comparison, separate research pegs NECB-2017 as about 5-9% improvement compared to NECB-2015 in British Columbia [EnerSys 2018], similar to the anticipated performance of NECB-2020. Thus, expected BC ESC Step 4 savings are 51-55% compared to NECB-2020, potentially less stringent than the 60% improvement of Tier 4 in NECB-2020.

COV standards are comparable to BC ESC Step 3 for buildings over 7 storeys, and Step 4 for lower buildings. The Higher Building Policy is aligned with BC ESC Step 4, the equivalent to net-zero energy ready construction.

## CONCLUSION

This paper has summarized four alternative "technical roadmaps" to net-zero energy ready construction, including the BC Energy Step Code, the proposed changes to the National Building Code and National Energy Code for Buildings and the Vancouver Rezoning Policy. The two significant differences were:

(1) The national codes are based on a hypothetical reference building of the same configuration being designed with prescriptive standards. Whereas, the BC ESC and COV have fixed energy performance references associated with a generic archetype building.

(2) The COV policy emphasizes greenhouse gas reduction, whereas the national codes and BC ESC emphasize energy efficiency.


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# JURISDICTIONAL RESPONSIBILITY FOR IMPROVING THE RESILIENCE OF BUILDINGS TO CLIMATE-RELATED POWER OUTAGES

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## ABSTRACT

This paper reviews the role of building codes, local municipalities and utilities regulators in achieving zero-carbon, climate resilient buildings, primarily drawing upon codes and regulations from British Columbia.

## INTRODUCTION

The costs of catastrophic losses – due to climate change and other factors – is increasing in Canada. In 2016, the insured catastrophic losses were over $5 billion, with the Northern Alberta wildfire causing insured losses estimated at $3.58 billion (Insurance Bureau of Canada, 2017). With global concentrations of greenhouse gases (GHGs) in the atmosphere continuing to rise, and increases in global average temperatures of 0.3 to 0.7°C expected for 2016–2035 (relative to 1986–2005; Kirtman et al. 2013), the need to make Canadian households and communities more resilient to climate-related acute shocks will continue to grow.

This paper is particularly concerned with the need to make Canadian buildings more resilient to disruptions in electrical power provision, whether arising from climate change related events, or other shocks such as earthquakes. The reason for focusing on electrical power is that use of electricity for an increasing amount of human energy needs is an essential strategy for reducing global GHGs and mitigating climate change. Provision of energy services causes the majority of global emissions, and the essential interlinked strategies for deep decarbonization of energy supplies are (IPCC, 2014; IEA 2014; Kennedy et al. 2018):

1. Decarbonize power supply (i.e., eliminate the use of fossil fuels in electricity generation).

2. Increase energy conservation and efficiency (i.e., reduce energy demand).

3. Fuel switching, either through electrification (i.e., substitute carbon-free electricity for fossil fuel use in engines, furnaces, among others) or use of other zero-carbon fuels (e.g., renewable natural gas, synthetic natural gas or hydrogen from zero carbon sources) for major end-uses. For the purposes of this paper, we will only focus on electricity, despite the potential climate and resiliency advantages of zero- or net-zero-carbon producing thermal energy resources.

Currently, Canadian provinces use electricity to meet between 10% and 40% of end-use energy needs. To reduce GHG emissions, provinces such as Alberta, Saskatchewan and Nova Scotia need to reduce the carbon intensity of their electricity supplies; and all provinces need to increase the percentage of electricity in end-use energy, beyond the 40% in Québec. This will require: increased use of electric vehicles for transportation; use of heat pumps for heating and cooling of buildings; greater use of electricity by industry.

From building science and energy end-use perspectives, the design of thermally efficient and air-tight building enclosures with heat-recovery ventilation, thermal-mass and "passive" cooling, heating and ventilation features, can help to cost-effectively minimize the demand for purchased energy and/or on-site generation.

From electrical and mechanical system perspectives, the use of "smart" appliances and controls to track electricity supply availability and pricing, along with high-efficiency HVAC equipment to minimize demand that is coincident with the utility peak, will further increase the cost-efficiency of electrification.

From a climate change adaptation perspective, however, increasing electrification is challenging, because it reduces the diversity of energy sources used in communities. Replacing fossil fuels with electricity – as is necessary – will decrease the variety of types of energy sources that households and businesses use, putting greater reliance on electricity and thereby making them more vulnerable to acute shocks. Moreover, as well as the diversity of energy sources being important, the ability to store energy in communities also makes them resilient (Bristow & Kennedy, 2013). Currently there is relatively little storage of electricity at the building scale, but this expected to change as costs continue to fall (Schmidt, et al. 2017). These issues also apply to other zero-carbon energy sources.

The solution to the dual challenge of climate change adaptation and mitigation is electricity generation and storage at the building or community scale. Due to climate change, future low-carbon electric communities cannot be exclusively reliant on high capacity overhead power cables bringing in electricity from distant sources. These systems are vulnerable to windstorms, fires and ice storms of increasing frequency. Provincial and sub-national electric grids will still be essential, but they need to be supplemented with building scale storage; and/or community-scale micro-grids; including perhaps power generation, the scale of which would be defined by the resilience timeframe sought in the event of natural disasters.

The question that this paper asks is who will take responsibility for building scale electricity generation and storage? The paper imagines a future where most buildings in a community have photovoltaics on the roof and/or a stationary back-up electric battery (including those in electric vehicles) capable of providing for basic building functionality over a few days following a shock event. The paper examines the possible role of building codes, local municipalities and utilities regulators in achieving this vision of a zero-carbon, climate resilient building stock. Much of the analysis of codes and regulations draws upon examples from British Columbia, though similarities with other provinces are expected.

## BUILDING CODES

Building codes are one potential means by which wide-spread building scale electricity generation and storage could be achieved. Current building codes in Canada and British Columbia do not explicitly consider building 'resilience,' albeit indirectly cover it through objectives of health, life-safety and fire and structural protection of buildings. They do not include electricity supply resilience. They do indirectly cover climate mitigation via energy efficiency, but not fuel switching.

The National Energy Code of Canada for Buildings (NECB), produced by the Canadian Commission on Building and Fire Codes with support from Natural Resources Canada (NRCan) is a starting point to consider. The current NECB (2017) describes technical specifications for achieving energy efficiency in new buildings, including control of air leakage, thermal transfer and limiting unnecessary consumption of energy for lighting, heating & cooling, water heating, and electrical equipment and devices.

The NECB includes functional statements of intent (National Research Council of Canada, 2017):

"F99. To limit the inefficiency of systems"; and

"F100. To limit the unnecessary rejection of reusable waste energy",

which could be possible opportunities to incorporate thermal energy or electricity storage into building codes.

A challenge with the NECB is that is tends to be conservative – providing a 'middle of the road' model for energy efficiency in new buildings, rather than tackling the leading edge. Some provinces go beyond the NECB in encouraging higher levels of energy efficiency. An example of this is the Energy Step Code in British Columbia (Government of British Columbia, 2019), which pushes towards net-zero energy ready buildings that use 50-80% less energy than the 2018 BC Building Code and include specific design guidance on resilience related to overheating and air quality.

Further work may be needed to introduce climate change mitigation and resilience as objectives of the National Building Code, substantially informing the content of provincial codes.

## MUNICIPAL GOVERNMENTS

Building owners are responsible for compliance with building codes. Local governments are delegated authority to elect to enforce building codes, and most require building permits for construction via local bylaws. Yet, even if resilience of buildings to power outages and other shocks is not considered part of the building code, there may still be some responsibility shouldered by municipal governments. This can be seen at a high level by examining the BC Local Government Act (Government of British Columbia, 2015).

Amongst the purposes of the BC Local Government Act (Part 1) is:

"c) to provide local governments with the flexibility to respond to the different needs and changing circumstances of their communities."

This broad statement alone is arguably a starting point for local governments in BC to increase the resilience of communities to climate change.

Looking further through the Act, the purpose of regional districts in BC (Part 5, 185) includes:

"(b) providing the services and other things that the board considers are necessary or desirable for all or part of its community,

(c) providing for stewardship of the public assets of its community, and

(d) fostering the current and future economic, social and environmental well-being of its community."

Items (c) and (d) here, give a mandate to local governments to consider the resilience of buildings within the community, and (b) points to the potential for municipalities to provide electrical power services (as is the case with New Westminster, Kelowna, Penticton, and a few other municipalities in BC).

Part 9 (section 298) of the BC Local Government Act provides further details of building regulation bylaws, the purpose of which are:

"(b) the conservation of energy or water;

(c) the reduction of greenhouse gas emissions;

(d) the health, safety or protection of persons or property."

These regulations provide further motivation for local governments to be more fully involved in building-scale electricity generation and storage. Furthermore, matters related to energy or water conservation or the reduction of greenhouse gas emissions are deemed "unrestricted matters" under the auspices of the Building Act, along with matters related to district energy systems (i.e., that could include zero-carbon supplies and micro-grids).

## UTLITIES REGULATORS

The generation of electricity in British Columbia, at any scale, generally falls under the authority of a utilities regulator. As in many Canadian provinces, British Columbia has a publically owned electrical utility, BC Hydro, which is the dominant distributor of electricity in the province, established by the Hydro Power and Authority Act. The only areas not served by BC Hydro are the City of New Westminster, and several municipalities in the central and south Okanagan, and the west Kootenay regions, along with the electrical service area of an investor-owned utility (IOU) FortisBC. Public utilities include electricity, natural gas, propane and district energy providers, but exclude municipally-owned utilities. Public utilities are regulated by the British Columbia Utilities Commission (BCUC). Currently several aspects of BC Hydro oversight are regulated directly by the BC Ministry of Energy, Mines and Petroleum Resources under the Clean Energy Act (CEA), but these aspects are being returned to BCUC oversight on March 1, 2021.

The BC Utilities Commission Act (UCA) (Government of British Columbia, 1996) stipulates the duties of the BCUC. At the highest level, these include (Section 5):

"On the request of the Lieutenant Governor in Council, it is the duty of the commission to advise the Lieutenant Governor in Council on any matter, whether or not it is a matter in respect of which the commission otherwise has jurisdiction."

This provision provides the Lieutenant Governor of BC with an entry point for transforming the utilities sector towards a low-carbon electric future.

More specifically, the BCUC provides oversight for:

• Long-term Resource Plans (LTRP) of public utilities (UCA section 44.1), generally for a 20-year timeframe, including "conservation" plans to reduce the demand for energy, load forecasting, and an assessment of supply needs. Since 2010, BC Hydro submitted its "Integrated Resource Plan" (IRP) to the government for approval, not under BCUC oversight.

• Expenditure plans (UCA section 44.2), generally for a 2-4-year timeframe, including forecasted capital spending for achieving LTRP conservation targets, building new LTRP supplies, or purchasing supplies from third parties. This includes BC Hydro capital spending but is subject to the requirements and exemptions of the CEA noted below.

• Certificates of Public Convenience and Necessity for the construction of public utility plants and systems. Several BC Hydro capital expenditures in their 2013 IRP are exempt from this requirement, including several clean energy plants (hydro, bio-energy, building-scale renewables, and smart meters) and strategic transmission lines.

The Clean Energy Act (CEA) (Government of British Columbia, 2010) establishes a path toward a low-carbon energy system with an emphasis on "BC Energy Objectives", "demand-side measures" (DSM) and "clean or renewable resources".

BC Energy Objectives of relevance to this paper include:

• To achieve "electricity self-sufficiency" – ensuring rights to electricity supplies to meet demands, assuming "mid-level forecasts", or average water conditions in hydroelectric supplies (Government of BC, Electricity Self-Sufficiency Regulation, 2012);

• To take DSM, including a target for BC hydro (see below);

• To generate at least 93% of electricity from clean or renewable energy resources, including biomass, biogas, geothermal heat, hydro, solar, ocean, wind, and additional technologies within the Clean or Renewable Resource Regulation (2011), including biogenic waste, waste heat, and waste hydrogen;

• To use and foster the development of innovative technologies;

• To ensure BC Hydro's rates remain among the most competitive of rates charged by public utilities across North America, thereby dispelling the myth that zero-carbon energy supplies are misaligned with economic efficiency;

• To reducing BC GHG emissions by 33% by 2020 and 80% by 2050 (note: this differs from the targets in the 2019 Climate Change Accountability Act of 40% by 2030, 60% by 2040, and 80% by 2050); and,

• To encourage fuel switching to lower carbon fuels.

The definition of DSM includes utility tariffs such as the "residential inclining block rate", programs such as Power Smart and FortisBC Energy Efficiency and Conservation, and support for government codes and standards to conserve energy or promote energy efficiency. DSM can also shift the use of energy to periods of lower demand. It explicitly prevents DSM that increases greenhouse gas emissions. BC Hydro is required to reduce its expected increase in demand for electricity (GWh) by 66% through DSM.

Shifting to the topic of resilience for buildings, there a number of drivers for BCUC jurisdictional oversight toward decarbonization and resiliency of the energy system as it relates to buildings.

First, the operation of buildings on zero-carbon energy supplies will benefit from technically achievable and economically optimized DSM. The 2013 BC Hydro IRP targets 78% of demand-growth through DSM, and BC Hydro (2019) documents that the recent cost of DSM is $0.019/kWh, well below the cost of new power supplies and rates (see below). Over 48% of the savings during the three-year period from 2017 to 2019 are from "codes and standards" in the provincial building code and provincial and federal government equipment standards. Benefit-cost ratios such as the "Utility Cost Test" documents DSM delivering benefits that are 3.6 times the cost of avoided supply, "Total Resource Cost" delivering consumer benefits that exceed costs by a factor of 2.4 to 2.7, and zero rate impacts of DSM, despite lowering demand.

Second, achieving GHG goals requires access to zero-carbon energy supplies. The BC Energy Objectives target 93% clean and renewable energy for all electrical utilities, focused primarily on utility-scale generation by BC Hydro and independent power producers. In 2018/19 BC Hydro electricity generation was 97.8% clean energy (BC Hydro, 2019-2). The subsequent Clean BC Plan (2018) includes a commitment to work with natural gas providers to put in place a minimum requirement for 15 per cent renewable content in natural gas by 2030. In 2019, FortisBC announced a goal to reduce its customers' emissions by 30% by 2030, noting that the cost of renewable natural gas is $0.06/kWh, compared with BC Hydro electricity at $0.09 and $0.14/kWh for step 1 and step 2 respectively (FortisBC, 2018).

Third, achieving "resilience" for the provincial energy systems to withstand acute shocks such as earthquakes and chronic stresses from climate change requires further consideration around response times for power outages such as the December 20, 2018 windstorm that left 730,000 customers without power, the most damaging in BC Hydro's history. Furthermore, climate change affects water resource availability which was 98% and 87% of average in 2018 and 2019 respectively (BC Hydro, 2019-2).

Fourth, achieving resilience at the building scale in light of more frequent power outages may justify on-site electricity storage, supplemental generation and sophisticated energy use controls to ensure that buildings are efficient and manage loads appropriately. The legislation and BCUC tariffs permit on-site renewable energy such as photovoltaics, enabled through the "net-metering" programs of electric utilities. In BC Hydro's case, this includes electricity billing the reflects the net consumption, "banking" for 12 months, and a payment for excess production at the end of the 12-month period, thereby serving as a "non-dispatchable" electricity resource for use by other customers. By extension, this could benefit from establishing micro-grids and the potential for shared storage and generation at a neighbourhood level, not currently promoted, but aligned with the "innovation" objective in the CEA. Part 3 of the UCA, on Regulation of Public Utilities, provides further provisions that are relevant to building-scale generation and storage of electricity. These include: a definition of a "person generating electricity for own use…; exemptions that the minister may make with regard to the production, sale, or purchase of power…; orders that the Commission may give to improve service…; and standards that the Commission may set".

As a final point, municipal utilities are exempt from the UCA. However, part 3 describes the important relationship with the Local Government Act, noting (in Section 121):

"Nothing in or done under the Community Charter or the Local Government Act

(a) supersedes or impairs a power conferred on the commission or a public utility, or

(b) relieves a person of an obligation imposed by or under this Act or the Gas Utility Act."

## CONCLUSION

Optimized energy efficiency, on-site zero-carbon energy generation, electricity storage and/or micro-grids need to be incorporated into buildings to both mitigate and adapt to climate change, but which jurisdiction should have responsibility for this transformation? Three were highlighted – provincial building codes, municipal governments, and utility regulators. There are key inter-dependencies that need to be unravelled to expose the optimal jurisdiction.

First, the question of provincial energy system resilience needs to be confirmed by the utility regulatory in order to determine the need for building and community-scale energy independence, despite the extensive efforts to decarbonize electricity and natural gas systems. Recent evidence of power outages highlights rationale for on-site generation and storage.

Second, given the inter-dependence between energy efficiency/load management and on-site generation, a question is raised whether these devices should be considered part of the building system, or not. If the answer is 'yes' then they should be included in the building code, supplemented with new National Building Code objectives for climate adaptation and mitigation and enforcement activities of municipalities; if the answer is 'no' then utilities regulators need to lead. In either case, the potential need for micro-grids and value of shared storage and generation necessitate a role for the utility regulator and by extension, municipalities given their mandate to own or host community energy systems.

Transformation of the utilities sector to address this challenge has many barriers, amongst them being the difficulty of finding business models that support distributed electricity generation (Kennedy et al. 2017). Solving this challenge is necessary for making our households and communities resilient to climate change. The BC Step Code for buildings is preparing the way for new buildings to be net-zero ready by 2032, but will municipalities, energy utilities and utility regulators be ready?

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# PLANNING AND SIMULATION OF NET-ZERO, CARBON NEUTRAL AND RESILIENT COMMUNITIES

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## ABSTRACT

An integrated urban platform is the essential software infrastructure for smart, sustainable and resilient city planning, operation and maintenance. Today such platforms are mostly designed to handle and analyze large and heterogeneous urban data sets from very different domains. Energy modeling and optimization functionalities are usually not part of the software concepts. However, such functionalities are considered crucial to develop zero carbon urban transformation scenarios and to optimize smart city operation.

In this study, we propose to develop a software architecture concept for an integrated urban data and modeling platform, which allows to analyze and optimize the urban infrastructure with their energy, water and further resource streams such as food or goods consumption. A methodology for extracting building geometry information at urban scale from CityGML and a framework for integrating building geometry with energy attribute data for urban energy modelling are proposed and discussed in detail. A first case study application is shown for renewable energy system design by considering two different scenarios using the Concordia University Campus, Montréal, and the obtained results are reported.

## INTRODUCTION

Supporting the planning and operation of smart and sustainable cities with a minimized $CO_2$ footprint is a huge challenge, as very different domain knowledge needs to be combined in an urban platform. Urban platforms mostly consist of data collection and analysis from very diverse sources such as sensors, municipal data records, knowledge repositories or social media streams (Celani et al. 2015). They make efficient use of the rapidly growing information and communication (ICT) infrastructure for collecting, processing, and sharing information (Yin et al. 2015). A reliable communication and networking infrastructure and big data handling can be considered as the backbone of smart cities (Rana 2018). At the same time, e-participation and smart technology applications offer new possibilities for citizen engagement and smart governance (Qing 2019), (S 2016). Smart city services rely on such urban ICT platforms, which offer seamless interconnection with monitoring systems at the infrastructure level. On top, storing and analyzing the generated information can eventually be offered to third parties through standardized interfaces as open data (Vilajosana et al. 2013). Urban data can then be used to validate physical or data driven models based on 3D geometry, which allow to develop ambitious zero carbon transformation strategies for a city.

## PROCESSING OF URBAN GEOMETRY DATA

### Extracting geometry information from CityGML

In this study, a fully automated python-based data pre-processing engine is designed to (i) extract the building geometry data from CityGML, (ii) query the data, and (iii) organize the data based on the input requirements of a building energy simulation engine such as EnergyPlus. The aim is to provide a user-friendly platform to integrate urban scale geometry information efficiently with other energy data and modeling tools. The exchange format CityGML represents the 3-D geometry and semantics of the buildings, transportation infrastructure, water bodies, and city furniture. The first step in the geometry extraction from CityGML includes collecting, analyzing, and restoring data. To map the footprint of buildings, at first, all polygons that belong to the respective building are merged. Besides, to create the 3-D model, the unified polygon of the buildings is extruded considering its average height. To reduce the computational runtime of the process, the 3-D geometry model is simplified (Figure 1). Subsequently, the extracted geometry data is enriched by other building characteristics such as year of construction and building type. One exclusive index is considered based on the central coordinate for each building to be easily recognized by the user. The building characteristics are assigned using this defined index. In the next step, building physics attributes are assigned to the buildings.

Finally, the enriched buildings' 3-D model with the attributes from other datasets along with the details on the occupancy model (based on the building typology classification) are created as an XML-based dataset.

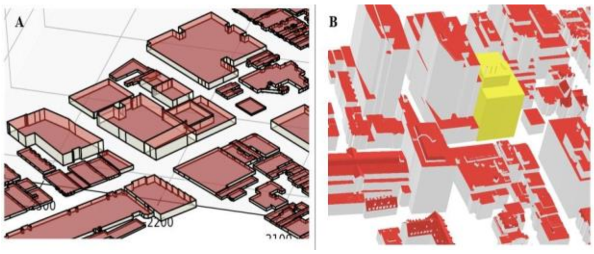


*Figure 1. Visualization of the Energy Plus input simplified 3D city model (left), city 3D model (right).*

### Generating input data file for energy simulation

To develop zero carbon strategies through improving the building stock energy performance needs a systematic evaluation of buildings individually over the temporal and spatial scale. The energy simulation of buildings on a large scale is done using a bottom-up engineering approach using archetype building modeling. Archetype modeling abstracts the building stock to a set of prototypes with detailed attributes for building physics, occupants and system operation. Each prototype is a representative model of buildings with similar characteristics, such as building activity, shape, and age located in the same climate zone. The US building archetypes (DOE, Commercial Reference Building Modeling) (DOE, Commercial Prototype Building Modeling) is a notable open data source provided on the national scale with in-depth details for EnergyPlus building simulation. The US Department of Energy (DOE) in collaboration with further national laboratories have developed 16 residential and non-residential building models covering 16 ASHRAE climate zones based on the commercial building energy consumption survey (CBECS) and supporting ASHRAE 90.1 (Deru et al. 2011). Since the properties of buildings are not widely available as open source data/public domain data, in this study, we leveraged on the US building archetypes to associate buildings with the appropriate archetypes carrying energy attributes.

Figure 2 shows the developed framework for integrating the building geometry with designed archetypes in the urban building energy modeling (UBEM) workflow. The input data to the procedure consists of the following,

- The geometric data with level of detail (LoD) LoD1 or LoD2 on CityGML format containing the spatial information.
- The building related data that includes building age, size, and activity type. Such details will be acquired from the Municipality or Governmental data sources. The matching of CityGML and building data provides the condition for connecting the archetype attributes.
- The designed building physics library covers the reference building archetypes, i.e., the archetypes with various refurbishment scenarios, and building components with regular ASHRAE 90.1 and advanced standards (ASHRAE 189.1-2009 and AEDG) for making new archetypes.

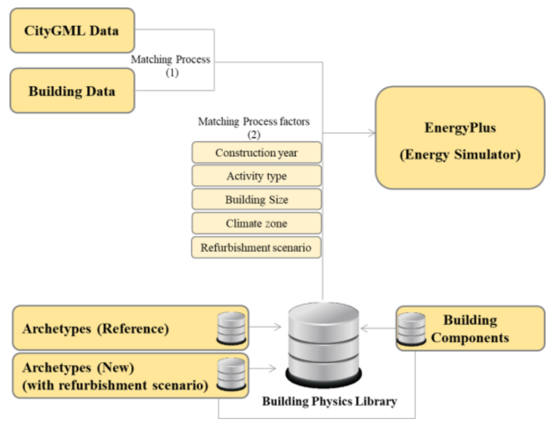


*Figure 2. Framework for integrating building geometry with energy attribute data.*

In order to simulate the heating and cooling loads, building models are necessary (Chen et al. 2019). The requirements of the building energy simulation are building geometry, internal gains (e.g., occupancy schedule, plug load and lighting energy consumption), and the climatic boundary conditions (Schiefelbein et al. 2019). Four datasets organize the structure of archetype models in terms of serving the dynamic energy simulation. The program category provides the required data to arrange plug and process loads, ventilation requirements, occupancy, and operating schedule. The form parameters identify the required geometric data coming from measured input geometry data (CityGML). The fabric property covers the constructional components and attributes plus the equipment category that supports the HVAC system, lighting, and control setting. Note that, in this study, we will use EnergyPlus to simulate the building energy loads. The enriched building with energy attributes or archetypes is connected to EnergyPlus using a geomeppy library in Python. Inputs regarding the occupant schedules for different building typologies are generated and the number of occupants is determined based on the buildings type. The output of the simulation including heating and cooling loads are visualized which could be used as a decision-making tool.

### Renewable energy system modeling

To implement an integrated renewable energy system at urban scale, there are several possible solutions, such as integrating different renewable technologies like wind tubines, PV or biomass. To compare solutions, the objective function can be varied and depends on the goal of the specific project. In most cases, minimizing the net present cost (NPC) of the system or cost of energy (COE) are used as the objective function.

## CONCORDIA UNIVERSITY CASE STUDY

### Downtown campus as a case study

Concordia University in Montreal has two campuses; Sir George Williams (SGW) and Loyola Campus, where the buildings of SGW campus are located in downtown Montreal. The main buildings of SGW campus are called EV, GM, MB, LB, FB and FG building. Although in this study the monthly cooling and heating demand of the buildings of the SGW campus is simulated (Figure 3, 4), considering the limited availability of measured energy consumption data, the EV building is chosen as the case study building and subsequently, the potential of renewable energy system implementation in EV under two scenarios were analyzed and the respective results are reported.

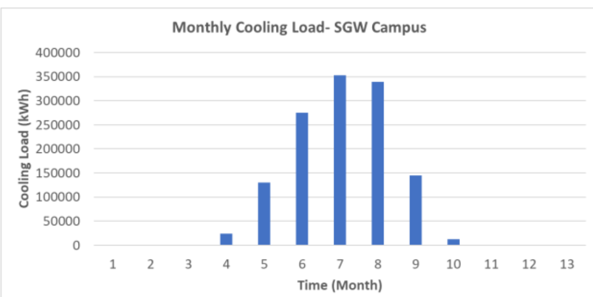


***Figure 3.*** *Simulation result of monthly Cooling demand of the buildings of SGW campus, Concordia University, Montreal.*

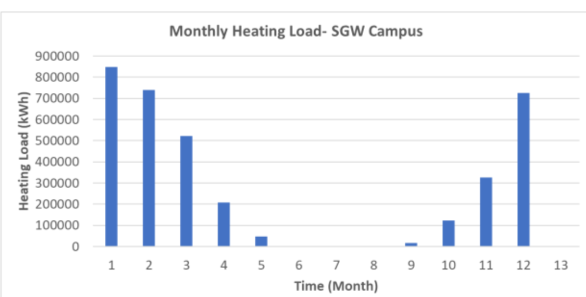


***Figure 4.*** *Simulation result of monthly heating demand of the buildings of SGW campus, Concordia University, Montreal.*

### Case study building (EV) description

With a gross area of 69,204 m$^2$, the EV building consists of Engineering Computers Science building (ENCS), and Visual Art and Science (VA) building, which are connected at different heights. The ENCS tower has 17 floors above the ground surface which includes office spaces, conference rooms, mechanical and chemical laboratories which are located in the 12$^{th}$ to 16$^{th}$ floor. On the 17$^{th}$ floor there is the mechanical room. Every three floors from 2$^{nd}$ to16$^{th}$ has an individual atrium. There are two underground levels that have a connection to the MB building, metro station, underground restaurants and a tunnel connecting to the Library building and Hall building. The VA tower has 12 floors above the ground including offices and workshops. The mechanical room is on the 12$^{th}$ floor. Note that the GM and MB building have gross floor areas of 22,663 m$^2$ and 37,935 m$^2$, respectively. Figure 5 and Figure 6 show the simulation result of the monthly cooling and heating demand of EV building that is calculated using the developed framework. In addition to geometry and construction material, occupancy and lighting are considered as the input to enrich the baseline model. For future work, the framework result needs to be validated by comparing the simulated result and actual energy data of the building.

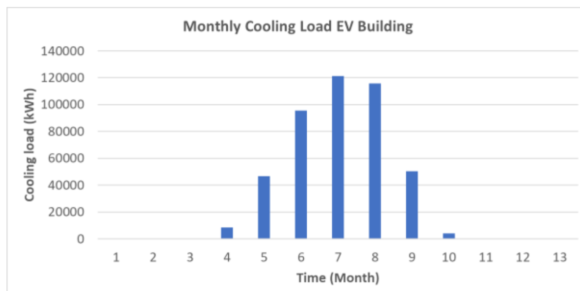


***Figure 5.*** *Monthly cooling demand of EV building, Concordia University located in downtown, Montreal.*

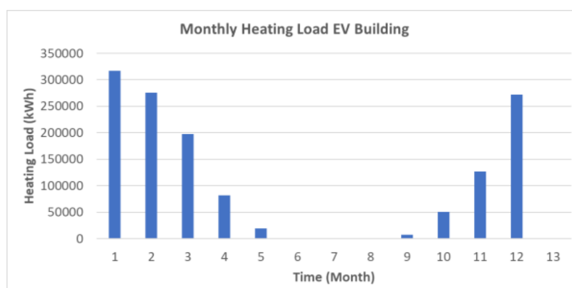


***Figure 6.*** *Monthly heating demand of EV building, Concordia University located in downtown, Montreal.*

### Renewable energy system concept for Concordia University EV building

In this section, EV building consumption is used to investigate the options for integrated renewable systems with two scenarios; (i) grid connected system and (ii)

100% renewable standalone system. In this research, the HOMER software is used as the optimization tool.

*Grid connected system:* Grid connection can solve the problem of the intermittent nature of renewable technologies and more importantly the challenge of storage since the high price of storage such as batteries could hinder its application in optimal energy systems. A complete grid rate schedule is used to consider different prices of purchasing and selling back to the grid in various times of the day and was applied for all weeks including weekends. Note that there is no interconnection charge as the Concordia University is already connected to the grid.

*Stand-alone system:* In this study, the stand-alone system includes PV, wind turbine, DC/AC converter and batteries. The wind turbine type considered was chosen based on low urban wind speed in Montreal. There are small 10kW wind turbines on the market with good power curves for low wind speeds that could be utilized for the location of Concordia University.

The comparison of both scenarios shows promising economic results. Three best cases were identified for scenario 1 (grid connected systems) and scenario 2 (standalone system) and the obtained results are presented in Table 1 and Table 2, respectively. The results show that grid connected systems are an even better economic alternative compared to the current energy system (purchasing from the grid) in case of net present cost (NPC) and cost of energy (COE)). In the grid connected system, the fraction of solar PV (solar fraction) is high at 79% of annual consumption of 37.4 GWh as shown in Figure 7. Considering the average price of 8-10 Cent/ kWh of electricity in Quebec (see Table 1), the cost of energy could be decreased around 40 -50% with grid connected systems and even less with considering solar tracker for PV systems. Table 2 shows that, for the second scenario, i.e., considering a 100% standalone renewable system with storage (Li-Ion Battery), the NPC and COE are relatively high and not cost efficient today. The main reason for the higher NPC for scenario 2 is because of the investment cost of the batteries.

Although the grid-connected scenario could bring down the cost of electricity significantly, lack of resilience and possible stress on the grid could be mentioned as one of the crucial challenges of using this scenario practically. Using batteries in a grid-connected scenario could solve the deficiency of resilience by increasing the reliability of the system for power supply in case of grid failure and power outage acting as a backup. Also, batteries could be charged in off-peak hours (in case of limitation for selling to the grid for bringing down the stress) when the availability of the renewable resources (solar irradiance in this research) is high and be discharged in peak hours in the time of electricity overpricing. An energy management system is mandatory for reducing the operational cost and proper management schedule based on the number of batteries and grid limitations.

***Table 1.*** *Considered cases for grid connected system.*

| CASE | PV (KW) | WIND TURBINE (10 KW) NO. | DC/AC CONVERTER (KW) | NPC ($10^6$ USD) | COE (USD/ KWH) |
|---|---|---|---|---|---|
| Case 1 | 19,635 | 0 | 12,123 | 30.7 | 0.052 |
| Case 2 | 20,617 | 1 | 12,533 | 30.8 | 0.051 |
| Case 3 (Grid only) | 0 | 0 | 0 | 36.4 | 0.111 |

***Table 2.*** *Considered cases for standalone system.*

| CASE | PV (KW) | WIND TURBINE (10 KW) NO. | BATTERY (1KWH LI-ION) | DC/AC CONVERTER (KW) | NPC ($10^6$ USD) | COE (USD/ KWH) |
|---|---|---|---|---|---|---|
| Case 1 | 111,630 | 0 | 151,754 | 4,735 | 166 | 0.506 |
| Case 2 | 20,336 | 708 | 103,020 | 4,948 | 102 | 0.311 |
| Case 3 | 0 | 2,021 | 253,396 | 13,269 | 224 | 0.683 |

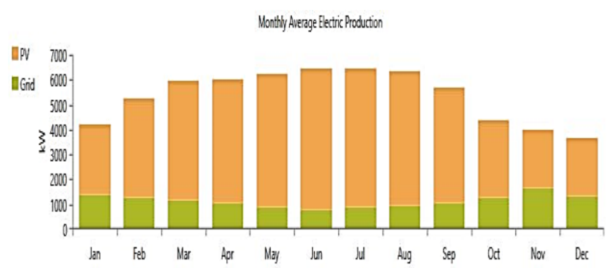


***Figure 7.*** *Monthly average electrical generation by PV and grid in scenario 1 (grid connected system.*

## CONCLUSION

At urban scale, buildings, commerce and industry as well as the transport sector are in the focus of the de-carbonization strategy. To develop such zero carbon transformation strategies for complex urban systems, we propose to model the buildings, energy supply and distribution systems of a city, calibrate the model with urban monitoring data and then to simulate transformation scenarios towards zero carbon cities. In this regard, a systematic procedure for extracting the building geometry data from CityGML and integrating building geometry with energy attribute data for energy simulation are proposed. The integration of renewable energy systems for a case study building of the Concordia University under two scenarios are investigated and the respective economical results are presented. The results show that the scenario 1 (grid connected system) is economically best suited for the implementation of renewable energy systems even when compared to today´s electricity purchase from the grid and even more when compared to scenario 2 (standalone systems). The proposed methodologies could be used for optimizing today´s infrastructure performance. A well-designed user interface and diverse 3D visualization features including virtual and augmented reality should enable access and involve citizens and local stakeholders interacting both in operation and strategic planning for sustainable cities.

## ACKNOWLEDGMENT

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# EXPANDING PERFORMANCE-BASED STEP-CODES BEYOND ENERGY EFFICIENCY USING A FORWARD-LOOKING REFERENCE BUILDING

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## ABSTRACT

Performance based codes often rely on energy modelling to demonstrate equal or better performance than previously established codes or standards. This paper proposes to flip the concept to a forward-looking approach where the reference building would represent a future high performance standard. This shifts the focus to a common future targeted performance level providing more guidance to all stakeholders of where the Code will transition to in the coming years. This paper discusses how this approach can also expand "performance-based" codes to areas beyond energy efficiency, to other performance attributes.

## INTRODUCTION

Governments around the world are continuously increasing the minimum energy performance of buildings as a way to help mitigate climate change. There are a number of challenges associated with having minimum performance requirements changing at every code cycle. It is difficult to provide training and education to industry stakeholders, developers planning a community do not know what performance will be required for different project phases, the supply chain needs to rapidly change, etc.

In an effort to help address these issues, the BC government introduced its Energy Step Code that sets out how the BC Building Code (BCBC) will transition from its current energy requirements to near net-zero energy requirements by 2032 in a series of stepped increments in minimum energy requirements (British Columbia, 2018). The idea is to advise all stakeholders how the BCBC will transition in the next 15 years so that stakeholders have ample time to prepare.

The BC approach is consistent with the Canadian government plans to develop a Step Code to help all jurisdictions transition from current energy requirements to a "net-zero energy ready" model building code by 2030 (Canada, 2016). The proposed change to the 2020 National Energy Building Code (NECB) has for four steps starting with matching performance to prescriptive code equivalent to requiring a 60% reduction in energy use in its last step (NRC, 2019).

There are two main categories of energy codes for buildings: prescriptive approaches that dictate the minimum performance of different building elements, and performance based approaches that rely on energy modelling to show that the building met a certain performance criteria. Performance based approaches can have absolute performance metrics (e.g. thermal energy demand, total energy use intensity, etc.) or they can rely on a differential predictive approach, which compares the performance of the proposed building to that of a baseline reference building (Rosenberg, et al., 2015).

Energy performance codes that use a reference building are easier to implement than setting absolute performance targets (e.g. energy intensity targets). Establishing absolute targets requires careful consideration of targets for different archetypes, and can be more sensitive to differences in energy modelling approach or software.

A reference building approach compares the modelled performance of the proposed building to that of a reference building with design parameters are set by the energy codes. The baseline has characteristics in three dimensions (Rosenberg, et al., 2015):

1. design parameters: prescriptive performance and design elements of reference,
2. time reference: year that baseline reference is established, and,
3. test criteria: relative performance difference that proposed building needs to achieve.

The architectural design of the reference building can either be dependent on the proposed building design or it can follow an independent rule-set. In a dependent design, the proposed building has the same form and shape as the proposed building but its efficiency is adjusted to meet prescriptive code values. The architecture of the reference house using an independent baseline is developed following a rule-set, developed based on floor area and building type (e.g. a set form factor, window-to-wall ratio, window distribution, HVAC system, etc.). There can be some combination, where some parameters are dependent on the proposed design (e.g. building shape), whereas others are independent (e.g. window area and distribution).

The time reference can either be fixed, where the reference code is established at a certain point in time and is not updated with code changes, or it can be set to the current prescriptive code requirements, which are updated at each code cycle. A stable or fixed baseline allows for easier tracking of code improvements, as the only thing that needs to change when increasing performance requirements is the relative difference in performance (e.g. requiring 40% energy savings instead of 30%). The fixed baseline also makes it easier to develop and maintain software that automate the generation of the reference building.

Test criteria indicates if the proposed building must be equivalent to the baseline (same energy use or cost than code minimum) or differential, meaning it must beat the reference by a set amount. When Rosenberg, et. al (2015) developed a roadmap for the U.S. Department of Energy for the future of energy codes for commercial buildings, they concluded that a differential predictive approach with a stable and independent baseline showed the best promise. It allows for a reliable comparison to a known baseline, normalizes the performance target to each specific building, enhances the ability to track improvement over time, paves the way for automated performance modeling, and markedly improves predictive accuracy.

Given the intention of a Step Code to transition building codes to a future energy performance standard, it would be more insightful to develop a reference building that represents the targeted future performance level. Instead of looking at a 10 to 20 year old energy code to set a minimum performance level that needs to be beat by 60% to 80%, the reference building could represent the desired future performance level that we are moving towards. This paper presents how this forward looking reference building approach could be implemented.

## FORWARD LOOKING REFERENCE BUILDING

This section describes how the baseline reference building could be defined using a future desired performance level. It is proposed that the reference baseline could use the following characteristics:

Design parameters: Quasi-independent design parameters that represent a desired outcome of the Step Code process.

Time reference: Static time reference set at the target date to reach high performance building standard.

Test criteria: for energy, develop targets of percent more energy than reference building, that would reduce for each step of the Step Code. Other test criteria could be developed to establish minimum performance levels beyond operating energy consumption.

In order to implement this approach, the building code committees would need to develop design elements that represents this future performance level. As part of the European Energy Performance of Buildings Directive (EPBD), Member States need to define minimum requirements of energy performance of buildings and building components with a view to achieving cost-optimal levels (Corgnati, et al., 2013). One approach used is to define reference buildings is to set prescriptive requirements to measures that lead to the lowest lifecycle cost. A similar approach could be applied to define the forward-looking reference building by setting it to the design that achieves the desired performance target at the lowest life-cycle cost.

### Architectural Design Elements

Architectural form can have a significant impact on energy consumption. There are a number of tools and methodologies that have been developed to maximize the performance of the form (Touloupakia, Theodosioua, 2017). A sophisticated methodology could be employed to find the site-specific optimal architectural form for the reference building. Alternatively, a more simplified method could be used that would simply use a form that minimizes the exterior envelope area to volume ratio ($A_e/V$) given the desired building footprint and floor area. Window areas and distribution could be based on standard window-to-wall ratios (WWR) with even window distribution by orientation or it could involve optimisation of the WWR by orientation to maximize performance.

It is proposed that the reference building utilize quasi-independent design parameters to account for specific site and/or project constraints that would prevent the proposed building from utilizing idealized design choices. The reference building definitions could allow for fixing certain design elements based on specific site and/or project constraints.

Potential site constraints could include adjacent structures or street orientations that may limit the allowable building and fenestration orientation. Geological and/or climate features could limit the type of foundation that is allowed. Bylaws may limit the total height of a structure. High wind areas may restrict the use of certain types of overhangs above windows. Project specific constraints could include things like a homebuyer requiring a single storey wheelchair accessible house. What is proposed is that if one of these constraints is present in a project, the reference building would implement the specific constraint in its modelling;

otherwise the standardized high performance design options would be selected.

**Building Envelope Performance Levels**

There could be a variety of approaches used to set the building envelope performance levels. Loukaidou, et al., 2017, assessed the lowest life-cycle cost performance levels for Cypress to meet the EPBD requirements. They found that the performance levels would vary based on the $A_e/V$ ratio where they found a linear correlation between optimal mean R-values and the $A_e/V$ ratio. However, the variation in optimal performance was not great, with the wall R-values increasing by a range of 5% to 11% when the $A_e/V$ ratio changed from 0.2 to 1.2. The reference building could have envelope performance levels that only vary based on climate zone, or they could also vary by architectural form and building type.

If the objective is to find building envelope performance levels for a reference building that achieves a net-zero energy target, the most cost effective performance levels will depend on mechanical system selection where heat pumps operating at a higher COP could lead to lower optimal envelop performance levels.

**Mechanical System Selection**

As mentioned, the choice of mechanical systems to use for the reference building will have an impact on setting other building parameters. If provincial or federal governments are going to achieve their 2030 and 2050 GHG reduction targets, there should likely be little to no natural gas used in new homes by 2030, and the electricity should all be coming from low to no carbon sources. A number of decisions would need to be made in order to define the mechanical systems for the reference building, including:

- Should it be limited to all-electric options?
- Should the default system be heat-pumps, and if so, what performance levels?
- When should cold-climate air-source heat pumps be specified?

**Renewable Energy Generation**

The federal and BC governments both aim to bring building energy performance levels to net-zero energy ready levels by 2030 and 2032, respectively. Neither code is currently being developed with the intention that onsite renewables could offset consumption. Whether a building can actually offset its energy consumption with on-site renewable energy to achieve net-zero energy consumption will depend on a number of factors such as solar access, roof size, climate, etc., with larger mid- to high-rise buildings typically not having enough surface area for renewable energy technologies to offset all of the energy consumption.

The forward looking reference building could model a solar photovoltaic system to meet a certain size (either in power [kW] or in area), completely fill roof surfaces that have favourable solar orientation, and/or achieve a desired performance level (net-zero energy or carbon, lowest NPV, etc.). In addition, the renewable energy systems could also be integrated into the building with battery storage to achieve resiliency targets such as a set amount of hours of back-up power.

The decisions around what to include in the reference building, whether for renewable energy, insulation levels or mechanical systems, would depend on the selected performance metrics to be used for the test criteria.

## ESTABLISHING NEW PERFORMANCE METRICS

If the broad objective for jurisdictions to implement energy efficiency requirements is to address climate change, energy-related metrics alone might not be enough. This section discusses how other performance parameters could be implemented within a future reference building approach.

**Greenhouse Gas Intensity**

Although reducing energy intensity is good, jurisdictions need to reduce their overall greenhouse gas (GHG) emissions. In the City of Vancouver, this was partially addressed by including a greenhouse gas intensity metric to their requirements, as well as capping the total emissions for large homes over 325 $m^2$ (3,500 $ft^2$), which must demonstrate a GHG footprint at or below that of a 325 $m^2$ (3,500 $ft^2$) home (VBBL, 2017).

**Net-Zero and Net-Zero Ready – Energy and/or Carbon**

As discussed, the federal government and the BC government both aim to bring building energy performance levels to net-zero energy ready performance levels by 2030 and 2032, respectively. Both have very broad definitions of what net-zero energy ready actually means, where neither code is currently being developed with the intention that onsite renewables could offset consumption. Net-zero energy performance levels are difficult to mandate as not all sites have a ready access to the sun, and larger mid- to high-rise buildings typically do not have enough surface area for renewable energy technologies to be able to offset energy consumption onsite. Net-zero carbon performance levels can be more feasibly achieved by different size buildings provided that a source of low-carbon electricity is available. If the intention is to get to net-zero energy ready, there needs to be a clear definition of what that means in order to be able to establish a reference building that achieves that performance level.

### Lifecycle Energy and/or Carbon

Other metrics could be used to compare the performance of a proposed building to a reference building to help inform design decisions. For example, is it better to build using concrete, which may be more resilient in the face of the increasing intensity of storms, tornados and hurricanes (Khanduri & Morrow, 2003), or out of wood to reduce the carbon footprint of our buildings (Gustavsson, Pingoud, & Sathre, 2006). Lifecycle energy and/or carbon estimates of the proposed and reference buildings could provide some guidance.

### Allowable Thermal Comfort

Looking beyond energy and greenhouse gas emissions at resilience, performance metrics could be used to compare the performance of a proposed building to that of the reference building to encourage more resilient design practices. During normal operation of the building, the number of hours that the reference building exceeds comfortable design conditions could be used as a limit for the proposed building. Similarly, during power outages, the interior temperature reached in modelling of the reference house after a set period (e.g. 72 hours) during both an extended cold period (minimum allowable temperatures) and an extreme heat events (maximum allowable temperatures), could be used to set the performance targets for the proposed building.

## MODELLING GUIDELINES

The required capabilities of energy modelling tools used to support the forward-looking reference building approach would depend on the selected performance metrics. Depending on the metrics, the tools and associated modelling guidelines, would need to be able to model the comfort requirements, life-cycle costing, embodied carbon, etc. In addition, current modelling tools rely on historical climate data for their calculations. Given the potential influence that energy modelling can have on building design, it would be best to model buildings with expected instead of historical climate.

## CONCLUSION

Instead of designing a building to beat an old standard by a certain amount, targets can be set as a percentage more consumption than the reference building or simply matching the performance of the high performance reference. This approach could have a number of benefits:

- Shifting the focus to a common future targeted performance level.
- Having a time independent baseline makes it easier to implement a number of future step improvements to the code.
- Could make selling minimum efficiency houses harder, given that it would be rated as a home that consumes ~400% more energy than the reference house, compared to current approach saying that it is 20% better than our current reference building.
- Opportunity to include other metrics to performance based codes.
- Provides a clear defensible methodology in developing high performance building metrics.


## ACKNOWLEDGMENT

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# DESIGN STRATEGIES FOR CLIMATE RESILIENT NEIGHBORHOODS

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## ABSTRACT

This paper presents a holistic approach to the design of climate resilient neighborhoods. Strategies discussed span from building level to neighborhood design level, encompassing elements such as building envelope design, integration of solar technologies in buildings and neighborhood surface areas, and integrated neighborhood energy systems. The paper highlights the role that interaction between various design factors play in achieving resilient communities, and the need of holistic design approach for successful design of resilient neighborhoods.

## INTRODUCTION

A climate resilient neighborhood is defined by its ability to rebound from climate-related shocks. Designing climate resilient neighborhoods is becoming increasingly urgent due to the frequency and severity of climate events, worldwide. The overall design of communities affects significantly their ability to resist disruptions, and their ability to continue functioning through extreme events. Mitigation and adaptation are the two main approaches that are employed in planning for resilience. Mitigation has been extensively studied, and is progressively implemented, primarily in relation to reducing energy consumption and associated GHG emissions of the built environment. Investigation of adaptation to climate change is still lagging, especially as related to the development and application of design strategies at urban level.

This paper presents some fundamental strategies in the design of neighborhood resilience, not just in mitigation of the effects of climate change, but also in adapting to this change and associated disruptions, such as risks of large-scale dysfunction. These strategies relate primarily to building design, to neighborhood characteristics and spatial design, and to urban and building energy systems. Discussion presented in this paper is based on extensive research on methods to enhance resilience of buildings and communities.

## BUILDING DESIGN

Building design plays an important role in overall energy performance and potential resilience. Design parameters including building type, building shape and layout, and building envelope, affect the energy consumption of the building as well as its potential to integrate solar technologies for renewable energy generation. Architectural design decisions including efficient building envelope with adequate insulation level, air tightness, window to wall ratio ((WWR) up to 40% on south facades, minimal on other facades) and high-performance window systems can reduce the energy demand for heating, cooling and daylighting, and thus the size of mechanical equipment. Design of various other features such as shading devices, light shelves, solar chimneys, and others can assist in optimal utilization of solar energy, reducing dependence on local energy grids.

**Building envelope design for energy generation.** Building envelope can be exploited to integrate solar technologies, such as PV and PV/thermal systems for the generation of electric and thermal energy. The shapes of the building and of the envelope affect the available surface area for PV and PV/T integration, as well as their exposure to solar radiation. While in low-rise buildings (≤3 floors) PV integration in roofs is dominant, in a multistory building integration of PV systems in facades offers advantage, due to the increased available surface area of facades, relative to roofs. Building shapes and

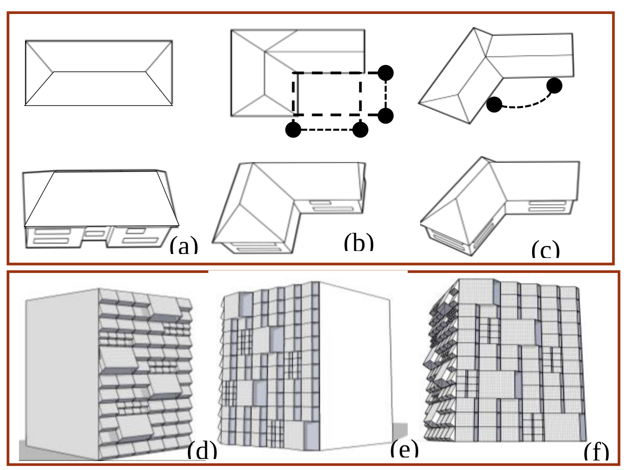


***Figure 1****. Manipulation in geometry of buildings for increased solar capture, (a-c ) building layout, (d-f) building facades.*

their orientations, and manipulation of self-shading building shapes (Fig 1b, c), affect solar accessibility of roof and facade surfaces, and their suitability for integration of PV systems (Hachem et al, 2011).

The geometry of building envelope can be manipulated to improve the electric and thermal output of the solar collectors. Modifying the tilt and orientation angles of some surfaces, independently of the shape and orientation of the building itself, can result in higher PV electricity yield. For example, a folded geometry of th ecan increase significantly the energy generation potential of roofs and particularly facades (Hachem-Vermette, 2018) (see Fig 1d-f). Such manipulations can provide creative architectural integration of PV systems.

**Passive design in buildings.** Passive design can be implemented in office and commercial buildings, as well as in residential buildings. For example, daylighting, passive heating of perimeter zones, passive and hybrid ventilation, coupling ventilation with solar chimneys, are design features that can significantly affect energy demand, reducing the buildings' dependence on the local grid.

**Energy efficiency measures.** Energy efficient lighting and equipment, including efficient mechanical systems are essential part of energy efficient buildings, which should be designed to complement the passive design. Efficient energy systems are discussed, below.

## NEIGHBORHOOD DESIGN

Neighborhood design plays an important role in improving its environmental impact in terms of net energy consumption and GHG emissions, and in enhancing the resilience of a community and its potential to adapt to various stresses. Some of the main factors that need to be considered are summarized in the following.

**Type of neighborhood.** A mixed-use neighborhood that includes various amenities within walking distance reduces the distance traveled per day, and therefore transport related energy use and associated GHG emissions. Such neighborhood presents a number of opportunities that can increase the energy resilience of the neighborhood. These include potential application of urban energy systems such as district energy, large-scale application of renewable energy, seasonal thermal storage and sharing energy potential between buildings, facilitating net-zero or even energy positive status.

**Impact of building mix**. The composition of building types within a neighborhood can significantly influence the amount of energy consumption by the neighborhood, as well as its potential to generate renewable energy from buildings and neighborhood integrated solar technologies. Research on the environmental and energy impact of building mix indicates that an optimal ratio of commercial land area to overall built land area lies in the range of 23% to 32 % (Hachem-Vermette and Singh 2019a). Residential buildings constitute the remaining part of the built area. This optimal range allows reducing the energy consumption and GHG emissions, while increasing the neighborhood's potential to generate non-fossil fuel based energy, to fulfill a significant part of its energy demand.

**Orientation of streets.** Street layout can affect the potential to capture and utilize passive solar energy, as well as the energy output of various solar technologies. Buildings should be designed to properly interact with street layout (e.g. orientation of main façade with respect to the street) without negatively affecting their energy performance. An example is shown in Fig. 2, where the design and orientations of buildings in various street layouts result in less than 3% difference in solar radiation incident on the main building surfaces (Hachem-Vermette and Singh 2019b).

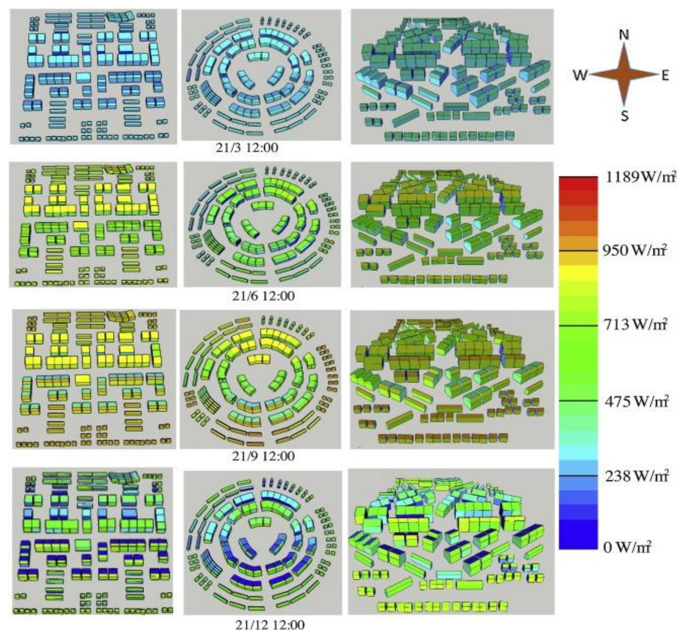


***Figure 2.*** *Solar radiation for 3 neighborhood layouts, during 4 representative days of the year.*

**Density.** Large number of studies associates an increased built density with urban environmental sustainability, especially at the city scale (Jabareen, 2006). In temperate and cold climates, where enhancing solar availability is a high priority, the negative impact of increased density can be counterbalanced through the deliberate manipulation of urban layout. For a given density, the level of solar radiation can be manipulated through combinations of site coverage and building heights (Lee et al, 2016). Increasing spacing between buildings allows better solar access to buildings, and thus increases their potential to utilize solar radiation for passive heating and daylighting, while also increasing solar availability at ground level. The impact of density as an isolated factor should be distinguished from the cumulative effects of various additional factors of a compact development, such as land use, transit accessibility, job availability, walkability and others (Hachem, 2016).

**Green and spatial areas.** Landscape can offer solutions for the integration of PV and solar thermal collectors in high performance resilient neighborhoods. New issues and opportunities arise in designing public open areas and landscape within the built environment for the integration of solar technologies (Fig.3a). Significant challenges are posed by the selection of public areas that offer an adequate solar potential, while avoiding shade from surrounding buildings. On the other hand, integration of solar collector structures in the public landscape provides the opportunity to improve the outdoor thermal comfort of the built environment. For example, PV structures can be employed as shading structures in urban landscape. They can be designed as charging stations for electrical vehicles, or as integral part of public parks to provide shading or rain protection (Fig. 3b, d). In addition, PV systems can be integrated along streets, fulfilling some functions such as noise barriers, while benefiting from high solar exposure (Fig. 3c).

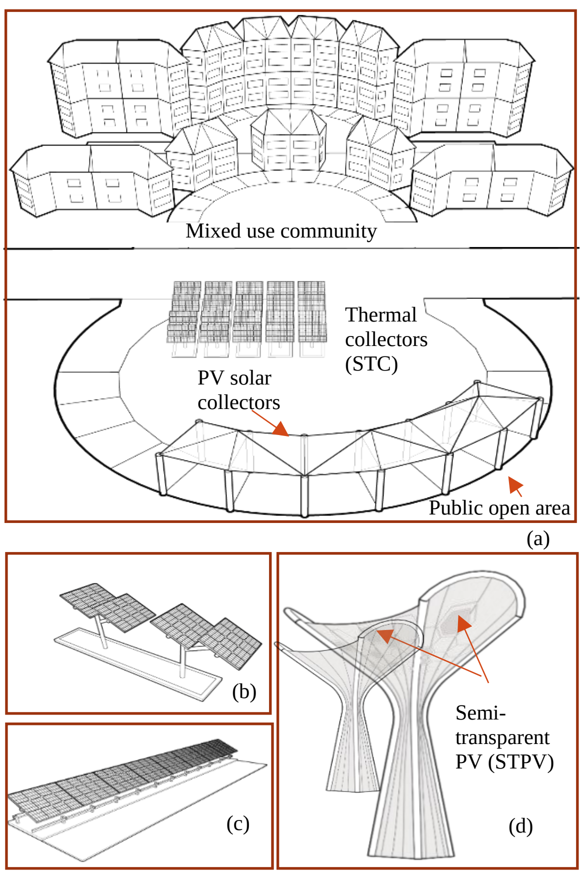


***Figure 3.*** *(a) Mixed use community with PV and STC integration in public areas, (b) PV as parking structure, (c) PV on street borders, (d) STPV in sculptural elements.*

**Street design.** Street design can affect transport mode and associated energy and GHG emissions. The availability of biking lanes can decrease the number of trips per vehicles and associated GHG emissions. Studies shows that the use of individual private cars can be reduced when designing streets with increased number of intersections (Hachem, 2016). Street design, including connection nodes and number of available routes, has significant impact on resilience of the neighborhood and potential evacuation during emergencies. Reducing the dependency on major streets constitutes a major criterion in the design of resilient neighborhood layouts, by avoiding the destabilization of the whole street network system when some of the central nodes are disabled. For instance, research shows that while a hexagonal street layout offers numerous advantages, some nodes of the street network are highly dominant, which may lead to disabling the neighborhood if such nodes are deactivated. The rectilinear street network, based on the fused grid design, is associated with a number of issues including longer distance between some nodes, and low overall efficiency, as well as restricted number of paths between some locations of the neighborhood. Such issues need to be addressed in the early design stage of a neighborhood (Hachem-Vermette, C. and Singh, K., 2019b).

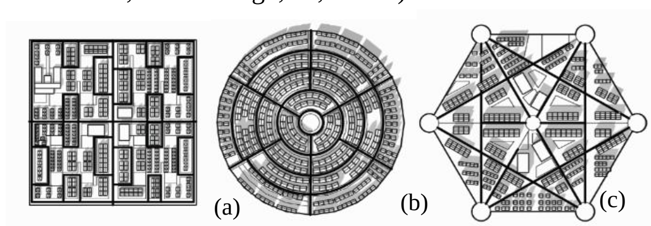


***Figure 4.*** *Three different street network designs, rectilinear (based on fused grid), radial and hexagonal.*

## ENERGY SYSTEMS

Resilient neighbourhood design should consider, in addition to the energy demand side, local and distributed energy generation strategies. A multiplicity of energy systems can assist significantly in avoiding functional disruption of the neighbourhood, during emergencies. Urban energy systems, both on the demand and supply sides, and their impact on neighbourhood resilience are briefly discussed below.

**Energy demand.** The architectural design of buildings, coupled with spatial neighbourhood design, can assist in reducing energy demand and in allowing buildings to exploit passive solar energy, increasing thus the capability of the neighbourhood as a whole to withstand chronic stresses and acute shocks. Energy consumption of buildings can be further reduced by employing high-energy performance mechanical systems. Methods employed to increase the efficiency of mechanical systems are in continuous development including heat pump technologies, heat recovery systems, different methods of ventilation (e.g. displacement ventilation), effective distribution and controls, and others. For instance, electrical air source heat pump (ASHP) powered by PV in combination with the local electric grid presents a viable, highly efficient solution for multi-storey buildings (Singh and Hachem-Vermette, 2020). Ground source heat pumps (GSHPs) can supply heat of up to quadruple the energy of the electricity they consume, by using ground-extracted heat. Smart control management systems enable preheating or precooling buildings before the peak hours. Preheating and precooling can be readily applied through strategic exploitation of thermal mass, highly efficient building envelope and controllable mechanical ventilation. Geothermal energy can be implemented on a large scale for energy production through a geothermal power plant. For buildings with heating-dominated energy consumption, the combination of a ground coupled heat pump (GCHP) system with a solar thermal system offers a high potential for energy conservation (Zhai et al, 2011).

**Energy supply**. Solar PV technologies, integrated in buildings and in various public open areas, form an important layer of resilience in case of utility energy disruption. Other energy systems can be exploited to increase the diversity of energy sources and provide additional layer of energy production for neighborhood resilience. For example, waste to energy (WtE) and small wind turbines can be exploited in mixed-use neighborhoods, alongside solar technologies (PV and STC) and borehole seasonal thermal storage. An optimization study of the mix of these energy sources, conducted for two concepts of a sample mixed-use community with the same composition and layout – a stand-alone community and a grid-tied community – indicates that a grid tied community is capable of achieving a net-zero energy status with a moderate size of renewable energy systems. Such self-sufficient neighborhood requires a thermal energy storage, coupled with solar collectors, together with PV installed in available south-facing roof areas (Hachem-Vermette et al, 2019). WtE and wind turbines, can be employed to supplement other renewable energy systems (e.g. PV and STC), especially when available surfaces for installing these systems are restricted. It should be taken into account that energy balancing and congestion issues may occur with the integration of increased levels of distributed energy resources. Integrated urban energy system should be designed to address potential congestion issues, allowing to manage energy generation, consumption, control and storage components.

## CONCLUSION

Planning climate resilient neighborhoods relies on a number of considerations, which need to be part of a holistic and integrated design approach, spanning from the building components level to the urban level, focusing on the interaction between these design considerations. Such approach should consider buildings and surrounding open public spaces as active elements of the energy network, consuming, producing, storing and supplying energy, rather than stand-alone energy consuming components of the grid. Consequently, all neighborhood components need to be designed to ensure continuous operation, energy efficiency and potential contribution to the urban energy system. For instance, street layouts can be designed to function in case of interruptions, while allowing near optimal orientations to enable passive and active solar design, enhancing thus the overall efficiency of the neighborhood. Additionally, building density can be determined to achieve various economic, social and environmental objectives, while not compromising the potential of open public spaces and building surfaces for integration of solar technologies.

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CAE Roadmap to Resilient Ultra-Low
Energy Built Environment with Deep
Integration of Renewables in 2050
Montreal Symposium, QC
October 16, 2020

# WIND RESILIENCE: PROCEEDING FROM WIND CODES AND STANDARDS OF BUILDING DESIGN PRACTICE

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## ABSTRACT

The central pillar of this paper revolves about how to employ resilience concepts in providing solutions for wind-related issues with emphasis placed on building issues. The regulatory provisions of the current wind codes and standards are addressed from resilience perspectives to identify their deficiencies. It is our belief that concentrating the efforts on these wind codes and standards could enhance the building resilience against wind.

## FUNDAMENTALS

Structures on earth exist within the lowest portion of the atmospheric boundary layer (ABL), which in itself is a major difficulty in wind engineering. Wind flow within this range is characterized as complex, wherein the turbulence level ($I_u$) is very high and the wind speed (V) is very responsive to earth surface topography and terrains. As shown in Figure 1, which provides a simple illustration for ABL over different terrain exposures, the wind speed within the ABL decreases as coming down to the earth's surface, but the turbulence increases.

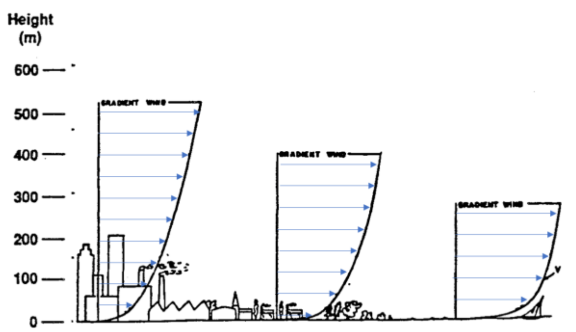
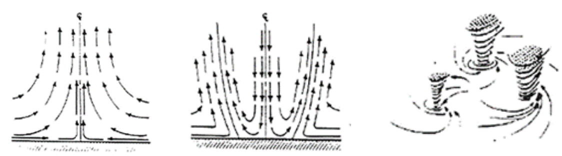



***Figure 1.*** *Illustration of mean wind velocity profile for sites of different terrain-exposures (Stathopoulos, 2007).*

Wind flow characteristics in strong-wind events (i.e., hurricanes, tornadoes, or downbursts) differ considerably from those of ABL. Examining the tornado flow interaction with buildings is even more marred by difficulties owing to the complexities of the tornado flows as compared with straight ABL winds. Tornado flows are characterized by swirling effects such as vortices with high tangential and vertical velocity components. Moreover, the structure of the entire tornado may consist of single-spiral, double-spiral or multiple-spirals (Davies-Jones, 2015 and Karami et al, 2019) with low-pressure zone (high suction) at the center of the spiral (Haan et al, 2008 and Karami et al, 2019) – see Figure 2.



(a) (b) (c)

***Figure 2.*** *Schematic illustration of (a) one-spiral vortex, (b) two- spirals, and (c) multiple-spirals (Davies-Jones, 2015).*

Building resilience is a forked concept encompassing numerous areas and aspects, including but not limited to energy and structural resilience. According to the resilience definition by 100 Resilient Cities Network (Pape-Salmon et al, 2017), these two aspects could be regarded as the core of the general building resilience since they are more directly involved with life permanence in the wake of acute shock occurrences like strong-wind events. Specifically, energy resilience concerns with promoting the energy self-efficiency of the building/community, while structural resilience concerns with occupation, serviceability, and functionality of the building itself and other renewables integrated or attached into the building.

The occurrence of strong-wind events is limited, but when they strike enormous loss of life, socio-economic, infrastructure and environmental damages might be left in their wake. Therefore, structural resilience against such events is a desirable goal to be promoted in order to maintain the three above mentioned characteristics of the structural resilience. Against this background, this paper discusses several points around the following questions: Where are the wind codes and standards with structural resilience? and shall we need to re-assess the current wind codes and standards? – with placing the National

Building Code of Canada (NBCC, 2015) at the center of debate as Canada is considered one of the countries exposed to tornados and other extreme winds.

## WIND CODES/STANDARDS

Wind codes and standards are fundamental reference sources for providing wind design provisions and regulations for structural engineers and practitioners.

Indeed, the current Canadian wind load provisions for buildings have undergone major developments and have been consolidated with extensive efforts devoted to the design pressure coefficients during the past 60 years. Canadian provisions are perceived to be innovative and ground-breaking by researchers and practitioners across the globe, thereby they have earned wide international recognition and reputation. Indeed, these provisions have contributed significantly to the development and evolution of various national and international wind load standards, namely: the American Society of Civil Engineers Standard (ASCE 7), the ISO wind load standard, the European Standard (EN 1991-1-4) and the China standard for Wind Loads on Roof Structures (JGJ/T, 2018) among others.

The NBCC provisions, as is the case with other international wind codes and standards, were formulated for normal wind conditions, i.e. straight ABL winds. Such presumption was not certainly intended to embrace a simplified or idealized approach but to provide a more appropriate framework for design purposes satisfying the safety and the economy of the design. The North American wind codes and standards (ASCE and NBCC) have generally been proven adequate, especially when treating low-rise buildings. Bearing in mind that low-rise buildings, mostly residential, industrial or institutional, comprise the majority of the structures on earth.

The interaction of ABL with structures is extremely complex, resulting in wind pressures on surfaces of the exposed structure spatially heterogeneous from point to point. The national wind codes/standards are based on the shape and size of the building, building openings, wind characteristics, surrounding environment such as nearby obstacles, and upstream terrain exposure.

Buildings with height less than 20 m and less than half of the smaller plane dimension are classified as low-rise buildings according to NBCC (2015). The wind-induced pressure (p) on external surfaces of such structures is defined as

$$P = I_w q_h C_e C_t \left(C_g C_p\right) \qquad (1)$$

in which $I_w$ is the building importance factor, $q_h$ is the reference wind pressure given as $0.5\rho V_h^2$, $V_h$ is the basic wind speed at reference height (h), $C_e$ is the terrain factor, $C_t$ is topography factor and $C_pC_g$ is the peak pressure coefficient. These factors among other wind codes and standards are discussed at great length by Stathopoulos and Alrawashdeh (2019).

The evaluation of the wind actions and effects on structures depends to a large extent on the estimation of wind speed at the concerned site. Together with wind engineering and structural researchers, meteorologists are also involved in this particular issue. The Canadian code (NBCC, 2015) demonstrates a sensible approach for describing the site. As indicated by Equation 1, the design pressure is derived using a variety of factors, most of which pertain to the site of the concerned structures. Both $C_e$ and $C_t$ are respectively accounted for adjusting the wind profile to be consistent with terrain exposure of the site and to speed-up the velocity due to the existence of escarpments or hills. Also, NBCC (2015) specifies values for the reference wind pressure (q) for several geographic locations across the country.

The code adopts the power-law, a model highly recommended for engineering application, to describe the ABL wind. Two surrounding terrain exposures are assessed on that basis, namely: Open exposure like a building situated on the periphery of open sea or lake, smooth land (without any noticeable obstacles, low vegetation) and open-land (isolated obstacles, low crops or plant covers); and rough exposure like a building situated in built-up areas such as areas with crops, plant covers, occasional obstacles, such as isolated low buildings or trees.

For cases involving sites of complex-terrain (e.g., buildings surrounded by urban or suburban areas of dense tall-buildings) and extreme climates, the Canadian code recommends wind tunnel testing – the same situation shared by other national wind codes and standards.

The peak pressure coefficients ($C_gC_p$), referred to in Equation 1, are related to the shape and size of the structures. Through the past five decades, a lot of research studies conducted to measure wind pressure coefficients on a variety of low-rise buildings, mainly utilizing the atmosphere boundary layer wind tunnels. The current pressure coefficients of North America wind codes/standards (NBCC, 2015 and ASCE 7, 2016) are virtually inclusive for most geometries and configurations of low-rise buildings (flat, gable, hip, mutli-span, and saw-tooth, etc). It has been recognized that hip roofs are given advantages over gable roofs for mitigating the exposure to high wind effects (Sandink et al, 2019).

## TORNADOS IN NBCC (2015)

In the past, assessing near-ground wind speeds of tornados commonly made through an indirect approach depending on the observed damages following the storm. Fujita Scale (F-Scale) is a case in point for that practice, which grades tornadoes on the basis of the intensity of wind damage – see Table 1. Mainly, difficulties of installing near-ground instrumentation in the path of a tornado were the reason for limiting the field measurements. Recent efforts aimed at further understanding the tornado and the surrounding environments through collecting data during tornadoes using mobile weather stations and radars (Bluestein et al, 2004; Blair et al, 2008; and Kosiba and Wurman, 2013). However, measurements at levels below 10-15 m are comparatively still scarce (Karen et al, 2014).

***Table 1.*** *Enhanced Fujita Scale (EF-Scale) and Fujita Scale (F-Scale) Wind Speeds (Information from Environment Canada's Weather Service).*

| Rating | Wind Speed (km/h) | | Damage Description |
|---|---|---|---|
| | F | EF | |
| 0 | 60-110 | 90-130 | Light |
| 1 | 120-170 | 135-175 | Moderate |
| 2 | 180-240 | 180-220 | Considerable |
| 3 | 250-320 | 225-265 | Severe |
| 4 | 330-410 | 270-310 | Devastating |
| 5 | 420-510 | > 315 | Massive devastation |

Tornadoes vary in the degree of intensity and severity. Canada adopts the Enhanced Fujita Scale (EF-Scale), which has been introduced by Environment Canada's Weather Service as an upgraded version of the Fujita Scale (F-Scale) – as compared in Table 1. Canadian tornadoes often occur in the season extending from April to September, although they could really strike any time of the year. They frequently develop in mid-afternoon to early evening.

Figure 3, which is included in the Commentary of NBCC (2015), shows the Canadian regions of vulnerability to tornadoes with the Fujita Scale (F-Scale) (Environment Canada: Sills et al, 2012). Clearly, large portions of the country are tornado-prone areas. According to Environment Canada's Weather Service, most of the Canadian tornadoes are F-0 by an estimated 45%; whereas, the rest tornadoes of scale F-1, F-2, F-3, and F-4 are estimated by 29%, 21%, 4%, and 1%, respectively.

As shown in Figure 3, three thresholds are established by NBCC (2015) to categorize the Canadian regions according to their vulnerability to tornadoes, defined by the probability of occurrence (PO) and intensity (F-scale), specifically: "prone to significant tornados", "prone to tornados" and "tornadoes are possible" for regions with F2-F5 (PO>$10^{-5}$ km$^2$/yr), F0-F2 (PO>$10^{-5}$ km$^2$/yr) and tornado observed (PO≤$10^{-5}$ km$^2$/yr), respectively. Notwithstanding the above, the probability of a building being struck by a tornado is very low, estimated at $10^{-5}$ /year.

Concerning low-rise buildings, the computational study of Lewellen et al (1997) and site measurements of Bluestein and Pazmany (2000) brought to light the fact that that the strongest winds exist within heights of 10-20 m above the ground with significant ramifications in evaluating wind loads produced by tornadoes, as that elevation range represents the height of most low rise-buildings (Haan et al, 2008).

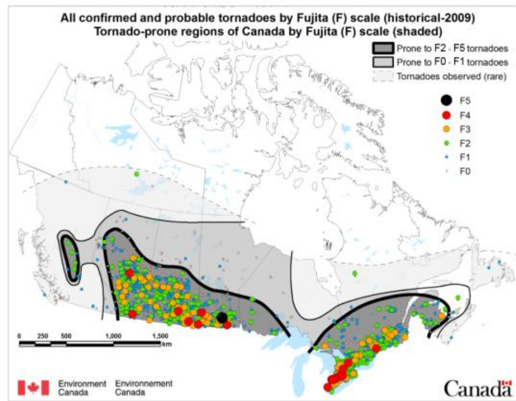



***Figure 3.*** *Map of all reported tornadoes in Canada between 1980 and 2009, identified by colored F-scale (Environment Canada: Sills et al, 2012).*

As indicated previously, developing the wind codes and standards for extreme wind conditions may be inefficient practice from building construction cost perspectives because of the "low risk of loss to individual owners" (NBCC, 2015). The Commentary of NBCC (2015) has recently included a basic set of measures in response to reducing tornado effects:

"The first detail – the anchorage of the house floors – is essentially covered by NBC Article 9.23.6.1. for typical housing with permanent foundations. CSA Z240.10.1, "Site preparation, Foundation, and Anchorage of Manufactured Homes," contains anchorage recommendations for protecting mobile homes against the effects of tornadoes. The second detail – roof anchorage in block walls – is essentially covered in CSA S305, "Design of Masonry Structures," through limit states requirements for wind uplift and, for the empirical method of masonry design, by Clause F.1.4 of the standard. Deficiency of this construction detail is especially serious for open assembly occupancies because there is nothing inside, such as stored goods, to protect the occupants from wall collapse. For such buildings in tornado-prone areas, it is recommended that the block walls contain vertical reinforcing linking the roof to the foundation. Key details such as those indicated above should be designed on the basis of a factored uplift wind suction of 2 kPa on the roof, a factored lateral wind pressure of 1 kPa on the windward wall, and a suction of 2 kPa on the leeward wall. "

## THE POSITION ON THE QUESTION OF WIND CODES AND STANDARDS RE-ASSESSMENT

It has been demonstrated that the engineered buildings are less affected by extreme winds. Tornado damage to a tightly connected building typically begins at roofs, façades and components and develops towards the interior walls, floors, and foundation. As illustrated in Figure 4, which schematically shows building components and supporting system in a vertical section, more attention is necessary for building integrity through preserving the wind pressure induced transferring along its path safely and smoothly, i.e., “continuous vertical load path” (Sandink et al, 2019). It is widely recognized that the loosening parts become more vulnerable to wind dynamics as the wind loads magnified due to their vibration. As a precautionary measure, periodic maintenance and check for inherent deficiencies in the building construction should be undertaken particularly for roof to wall connections. Also, further construction detailing measures may be undertaken. A case in point, a change in the spacing of roof sheathing fasteners of intermediate supports from 300 mm to 150 mm, driven by increasing the resistance for high wind like tornadoes, was made into the Ontario Building Code (OBC, 2010).

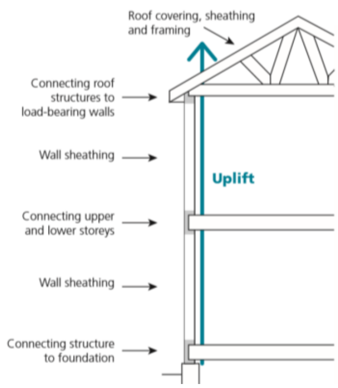



***Figure 4.*** *Building vertical section showing the components and load path (Sandink et al, 2019).*

Recently, some structural and wind engineering researchers have embraced the strategy of applying resilience for buildings of public service facilities, such as hospitals, educational institutions, airports, and power plants. In this regard, the buildings of such facilities shall be designed for severe tornados (i.e., F-3 intensity of mean wind speed 250-320 km/hr) or higher (Haan et al 2008).

Finally, more action and measures on the reference design basic wind pressure ($q_h$ as referred in Equation 1) may be taken to further raise the wind resilience through wind codes and standards. The maximum $q_h$ value to be found in Appendix C of the NBCC (2015) is 1.23 kPa (at Resolution Island, Nunavut for a return period of 50 years); whereas, the vast majority of the values found to be ranging from 0.30 - 0.70 kPa. It could be suggested that these values of $q_h$ may be revised and magnified to accommodate the risk of F-2 tornado pressure forces (which covers the occurrence of 75% of the Canadian tornadoes), particularly in dense population regions. In these cases, wind measurements at meteorological stations and special wind tunnel simulations must certainly play their part.

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# BUILDING OPERATION AND OCCUPANT BEHAVIOR

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## ABSTRACT

This paper discusses "building operation and occupant behavior" in the context of developing a Canadian roadmap for resilient buildings. Two questions are explored: 1) what is the role of building operators and 2) what tools can help with the process of learning from buildings over their lifecycle? These questions were chosen because they are real-world questions that emerged from a series of post-occupancy evaluations, they are under-studied or newly studied in the scholarly literature, and they appear to converge upon an important component for the roadmap for resilient buildings.

## INTRODUCTION

The 2019-2021 "Canadian Roadmap for Resilient Buildings" process of three symposia has taken on the task of finding solutions that address the three objectives of resilience, deep reductions in GHG emissions, and optimized energy efficiency plus on-site renewables. This paper, prepared as a contribution to the second symposium, addresses the topic of "building operation and occupant behavior", specifically focusing on the building operator as building occupant. The paper enlarges on two questions that emerged in the course of a series of post-occupancy evaluations of green buildings carried out between 2002 and 2014: 1) what is the role of building operators and 2) what tools can help with the process of learning from buildings over their lifecycle?

## FOCUS ON BUILDING OPERATORS

The title of this paper references "occupant behaviour". Building occupants include those few whose core role is managing the building and its systems, and those in a larger group whose primary reasons for being in the building are other than assisting in its operation. The behaviour of the latter is being studied by other contributors to this symposium. The behavior of the former will be described and discussed here.

Interviews with building operators during post-occupancy evaluations prompted this exploration. Many buildings have building operators, and operation and maintenance activities have a strong influence on energy use in buildings (Gazman 2012), but the role of building operator is not consistently defined or frequently studied. In Canada, there is no unique National Occupation Classification (NOC) code for "building operator", due to the diversity of related roles. The number of actual building operators in Canada was recorded as "unknown" in a 2011 study (EcoCanada 2011). The same study defined a building operator as "a person who has the appropriate skills needed for the day-to-day maintenance and operation of large facilities that have complex heating, mechanical, and electrical systems along with specific knowledge of how to operate the facility in a way that takes into consideration the interplay of building systems to maximize energy and resource efficiency, reduce waste, provide superior indoor air qualities, and the requirements of building tenants" (EcoCanada 2011). For comparison, "Facility Manager" can include building, facility and maintenance managers (Hughes 2017). Some sources do not distinguish between "building operator" and "facility manager" (for example, Bernardo 2019).

In the United States, a federal level process has examined the requirements for every job classification in the building design and operation field (37 by their count) through the lens of competence in building science and have identified "Buildings Operations Professional" as the one who "manages the maintenance and operation of building systems and installed equipment, and performs general maintenance to maintain the building's operability, optimize building performance, and ensure the comfort, productivity, and safety of the building occupants". The process aims to develop voluntary national guidelines to improve the quality and consistency of commercial building workforce credentials, and to clarify pathways for workers to strengthen their credentials through accredited training, including for example the Building Operator Certification (BOC®) program delivered in many states (Metzger 2017). Those advocating for the improved process note that many building operators simply learned from the previous person in their role, some had not taken an exam for twenty years, and that utility subsidies were important in making training financially accessible (Gazman 2012).

Despite increasing automation and availability of data for training machine learning systems, many buildings continue to rely upon human operators; in 2017, only 14% of buildings in the United States (43% of conditioned space) had any kind of building automation system (Katipumala 2019). Even enthusiastic promoters of digital transformation of buildings recognize that "we still need experienced and knowledgeable staff" (Woodhead 2017).

Labour market research indicates that human operators can be hard to find. For example, the real estate industry provides many jobs in building operator roles, to manage commercial buildings. However, recruitment and retention are challenging and urgent given the aging workforce. A recent BC study indicated that the industry perceived itself as underserved and not well understood by post-secondary institutions in terms of its needs for qualified workers; at the same time, its practices around credentialing have been inconsistent and may not have established clear standards for candidates, while the candidates may be seeking careers that are more technology-driven and that offer "work-anywhere" conditions. The top ten skills identified as lacking among the talent pool included smart building technical knowledge, energy conservation knowledge and leadership skills (BOMA-BC 2017). As reported in the US process mentioned above, challenges facing the US building energy efficiency workforce include lack of early career interest, lack of diversity, fragmented preparatory programs, and difficulty recruiting. In Canada, difficulty in getting leave for training has also been identified as a problem (EcoCanada 2011).

## OPERATING RESILIENT BUILDINGS

This section reviews expectations that are placed on building operators under conditions that require resilience, i.e., "the ability to prepare and plan for, absorb, recover from and more successfully adapt to actual or potential adverse events" (GAO 2015).

A building placed in service today will be cared for by building operators until it is taken out of service, possibly as far out as the next century, through all the changes and adverse events anticipated in these coming years.

Upon handover, the design team and construction team normally exit, leaving a set of documents or a digital dataset with the building operator to support building operation and maintenance; this can be the first involvement that the operator has with the building, though it is recognized that including the operator in the design process can improve outcomes in building performance. In some cases, the building is commissioned, typically by a third-party agent who ensures that the building is functioning properly when started up and who may carry out some training with the operator. After the commissioning work is completed, the building operator and their reporting hierarchy carry forward the responsibility for ensuring regular recommissioning, recommended at 3 to 5-year intervals. Recommissioning can pay for itself by reducing wasted energy, but like commissioning, it is not well understood by decision-makers among the building owner groups.

Both commissioning and recommissioning, while rewarded within resilient building rating systems, may need to be advocated to building leadership by building operators (Min 2016). In cases where buildings have not received commissioning prior to occupancy, the building operator may need to recommend retro-commissioning to management.

During the building's service life, it is likely that its operators will need to respond to conditions that test resilience. According to Hewitt *et al.* (2019), "Buildings exist primarily to shelter vulnerable people from the external environment". However, in some cases, buildings may not be able to fully withstand shocks that they receive, resulting in three end-user experiences of building condition: typical building operations, atypical building operations (in adverse circumstances) or building failure. For example, during Hurricane Sandy, the well-known Battery Park building was able to continue operating because its substation (located in a rebuilt section of the World Trade Centre) was not flooded, and the building's electrical equipment was on a high enough building level to escape water incursion. Its stormwater reservoir and wastewater treatment plants were shut down as had been planned in advance, so it was operating in an atypical condition, but it did not go into building failure. Because of highly effective work by building operators, residents were able to return to the undamaged building in a short time, hastening their recovery from the extreme weather event (Hewitt 2019).

To continue to "shelter vulnerable people", even if in atypical building operations, buildings need to be resilient. Also, the buildings' operators need to have skills for resiliency. Phillips et al. (2017) recently reviewed four resilience rating frameworks and grouped into themes the 88 strategies that they developed. The themes are Risk Avoidance, Passive Survivability, Durability and Longevity, Redundant Systems, and Response and Recovery. At least three of these themes directly recruit the competencies and leadership skills of those in charge of operating the building.

For Passive Survivability, renewable energy systems require skills in operating, maintaining and integrating the energy system in normal operation and possibly in different modes in atypical operation. For example, the presence of PV systems complicates the challenges for building operators to avert demand charges related to building electrical load peaks (Zhang 2018).

For Redundant Systems, the operation of back-up generators and water supply systems requires specific skills. For Response and Recovery, the ability to resume operation quickly post-hazard requires leadership ability and competence in connecting with local networks.

In general, decision-making at the building operation level during or after an adverse event is a challenging task that may require time-sensitive discernment about whether the building will be able to resume operation.

The US federal process mentioned above recognizes building operators' growing scope, and explicitly names, among core competencies, the need to understand building resilience, natural or man-made disasters, and onsite energy generation. Considering the level of responsibility for building operators in all buildings and especially in sustainable and resilient buildings, the proposed roadmap to resilient buildings for Canada needs to include, similarly, provision for support to this group in terms of recruitment, training, certification, and visibility of their role. Consistent certification of building operators in specific roles (categorized by size of building, complexity of systems, scope of duties, responsibilities in adverse events) could strengthen public recognition of these career paths and promote appropriate compensation as well as inclusion in design processes. As the built environment changes through pressure to be more sustainable and resilient, buildings may require much more sophisticated skills than at present to operate optimally; professional engineers may take to specializing in building operation in their undergraduate programs and beyond. Canada cannot have real resilience in the built environment if the building systems are not understood, maintained and implemented correctly by skilled building operators.

## FOCUS ON LEARNING FROM BUILDINGS

The second question being considered in this paper is, what tools can help with the process of learning from buildings over their lifecycle? This question moves the discourse from human solutions (building operator) to technological solutions (software tools for sharing information). Over the past half century, techniques for evaluating building performance have been developed and applied, including many called in general "post-occupancy evaluations" (POE). These techniques have been used to study the occupancy phase of the building lifecycle, including "assessment of building performance, exploration of relationships between inhabitant behavior and building resource use, optimization of the indoor environment for inhabitants, more informed decisions about future building design, and opportunities to enhance the dialogue within design teams and their partners" (Li 2018).

A frustration for post-occupancy evaluators is what has been called the "3-ring folder POE" – the document that gathers dust when a study's results have not been integrated into architectural practice or building operators' methods (Goçer 2015). To date there have been few ways that designers could conveniently integrate the findings from POEs with their own experience – for example, they could read reports, attend presentations about completed studies, or explore the results of occupant satisfaction surveys in comparison with reference datasets (Huizenga 2006). Only a small minority of buildings receive evaluation, so the random chance of a designer having the opportunity to learn from an evaluation of a building they have worked on is small.

However, increasing digitalization of the construction industry may address the problem of unused POE reports as Building Information Modelling (BIM) features become fully implemented and as advances in Internet of Things (IoT) provide more opportunities for data to be gathered, either from occupant feedback or from onsite sensors. According to Tang et al., (2019):

> By incorporating geometry, spatial location and a scalable set of metadata properties, BIM models provide a high-fidelity operable dataset capturing the as-designed building objects, properties and spatial organization as a set of virtual assets. IoT data enhances this information set by providing real-time and recordable status from the actual operations in construction and operations.

With the continuing development of the full functionality of Building Information Modelling (BIM), emerging information can be associated with every aspect of the as-built computer models of the building. This can include: all information learned about the building from inception to end of life; all model and IoT sensor data throughout the building life as well as virtual reality systems and automation systems; all data from other aspects of the construction industry, integrated through the development of interoperability standards, and used for shared purposes such as facility management; all information needed to operate the building with minimum energy and emissions. From the perspective of the building operator, an enhanced resource for guiding operation is created by feeding all this information into the as-built model, and the information can be displayed in a three-dimensional form (either using BIM or alternative software as described in (Motawa 2013) or (Lee 2019)) to help clarify where salient features are located in the building.

The information can "flow forward or back", that is, it can be used by design teams to learn (through post-occupancy evaluation results) from the outcome of their past design decisions, or can be used as a reference for future operation of the building. Appropriately curated, the information can theoretically "flow sideways" to other building operators and other design teams in the same company or (in a spirit of collaboration) other companies. From a knowledge management perspective, the arrangement of relevant information into the three-dimensional representation of a real project, as explored by (Jaffery 2016), can potentially engage and inform all those who are concerned with the project. The diverse professional dialects and file formats (as outlined in Dibley 2012) that may have impeded interdisciplinary relationships in the past can be circumvented so that information is able to flow into understanding and knowledge for all participants. This kind of construction industry collaboration is classified as "BIM Level 2".

A higher level, BIM Level 3 (also referred to as iBIM or "integrated BIM"), is foreseen that would open possibilities for interacting and collaborating through distributed ledger technologies (DLT, i.e., blockchain). According to Li et al. (2019):

> The integration of BIM, DLT, smart contracts and the IoT can have a significant impact on construction activities and facilities management, especially where tracking of components proves useful and where there is duplication of work; IoT tracking devices will automatically collect data regarding an item or a process and update the ledger accordingly.

Arup (2017) suggested that Level 3 BIM capability may be still "a few years away". In 2018, the Hackitt report on the Grenfell Towers fire in Britain recommended that a controlled digital record such as would be made possible by distributed ledger technologies should be required at handover in a building design and construction process (Li 2019). By 2020, a Canadian/Australian research collaboration produced a proposed modular information management framework that could form the basis for a blockchain-enabled system to improve construction processes (Succar 2020). On the other hand, a different 2020 Canadian-authored paper outlined the existing barriers to streamlined construction processes: "outdated BIM, disconnected trades, lack of terminology, insufficient documentation, inefficient transitions across views and artifacts, unavailability of design information, information discrepancy, unfit navigation tools, and office–site disconnect" (Mehrbod et al. 2020). ARUP (2019) estimates commercialization of BIM blockchain technologies to start around 2027, and adoption to occur around 2035, but recognizes that these predictions may be inaccurate. In summary, despite significant pressure and rapid disruptive technological development, the goal of automatically integrating post-occupancy evaluation results into single shared DLT-based building models may still be remote. However, as off-site modular prefabricated construction becomes more widely implemented, the design cycle for buildings may be expected to be more like automobiles, with user results from present models feeding into design for future models through the iBIM route.

## CONCLUSION

This paper has addressed areas of inquiry that emerged through a series of post-occupancy evaluations. The role of building operators in resilient buildings was explored, with the recommendation that a stronger system for building operator certification in Canada is needed to make buildings more resilient in use. The challenge of learning from the full life-cycle of buildings was described, and possible technological solutions were proposed. Of these two action areas, the building operator training opportunity may be faster to implement. If training includes BIM and iBIM skills, the renewed role of building operator can include using these technologies to channel findings about building performance to designers, as an integral part of Canada's roadmap to resilient ultra-low energy built environment.

Further research and reflection are needed on the implications of the problems and solutions proposed above, in particular the extensive use of building information modeling as a way to learn from buildings in use. At present the building design and construction industry is unevenly mediated by technology. Using advanced data management and visualization techniques to collate post-occupancy research findings may lead to rapid steps into machine learning, that may outpace the capacity of humans to become better building operators. Computers may make decisions about building operation that would differ from those that humans would make. In parallel with national public sector leadership needed for improved building operator certification, governments at all levels may need to provide improved regulation for decision-making for human health in buildings.

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# THE CHALLENGES OF DEVELOPING THERMAL RESILIENCE POLICIES, PROTOCOLS AND PROCEDURES FOR BUILDINGS

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## ABSTRACT

The recent recognition of the need for greater resilience of our built environment in the face of climate change and other natural and anthropogenic disasters has spurred numerous research efforts around the world. As a growing proportion of the global population lives in cities, and the frequency and severity of extreme weather events escalates, it is important to put research findings into practice. This paper presents an example of translating thermal resilience research into public policies, protocols and procedures that can be adopted presently and then implemented strategically over time.

## INTRODUCTION

Resilience of our built environment hinges on a large number of interrelated factors that differ across geographic and climatic regions, as well as between cities, towns and rural communities. One critical determinant of resilience is *passive survivability* - a building's ability to maintain critical life-support conditions in the event of extended loss of power, heating fuel, or water. Passive survivability involves a number of aspects including thermal moderation, water, food and emergency medical supplies - it speaks to a prolonged power outage resulting from an extreme condition which could be related to a severe climate event, infrastructure crisis or conflict situation (Wilson, 2005). Examples of outcomes stemming from inadequate passive survivability include hypothermia, heat stroke, water shortage, food spoilage, freezing/bursting of water pipes, computer system meltdowns/flooding, etc. It is an extreme condition with serious negative consequences for the occupants, the building, its equipment and contents.

Thermal resilience is an aspect of passive survivability in buildings that is commonly assessed using two metrics: *thermal autonomy* (TA) is a measure of the fraction of time a building can passively maintain comfort conditions without active system energy inputs; and *passive habitability* (PH) is a measure of the duration of time that an indoor space remains habitable following a prolonged power outage over an extended period of extreme weather, hot or cold.

This paper focuses on policies, protocols and procedures needed to enhance the passive habitability of social housing recognizing that such measures must be nested within a broader framework of resilience planning that itself must respond to the particular context of the community it wishes to shelter and protect when extreme weather events and/or disasters strike.

## CONTEXT

Service de l'Habitation, Ville de Montréal engaged Danny Pearl and Amy Oliver of the local architecture practice L'OEUF to explore the potential for enhancing the resilience of its existing and future social housing projects. Ice storms and heat waves over the past several decades have revealed the vulnerability of this housing stock for a population that is economically challenged to fend for itself under crisis conditions. In turn, engineers Yan Ferron and William Harvey were retained to provide technical assistance under a framework developed by Professors Ted Kesik and Liam O'Brien. The purpose of the study was to develop a report containing recommendations for how to enhance the thermal resilience of Montreal's social housing, both short-term measures and long-term strategies.

## PROCESS

The process began with a review of the principles and concepts advanced in two publications: 1) the *Resilience Planning Guide* (Kesik, 2017); and 2) the *Thermal Resilience Design Guide* (Kesik et al., 2019). The first publication provides a broader framework for resilience planning and risk management. The second publication provides for technical design and analysis of thermal resilience measures in buildings based on previous research (Ozkan et al., 2019).

Then, using existing social housing projects constructed in Montreal that had been designed by the architects undertaking the study, the engineers that were retained conducted thermal resilience analyses, in particular, assessments of the passive habitability of the buildings under both extreme cold and hot weather scenarios.

The information gained through the analyses could then be input to a framework of thermal resilience protocols and procedures as outlined in Figure 1. It could also be used to assess the current thermal performance of social housing technical standards to determine if these are adequate.

**Inventory and History**
Take an inventory of first responder capabilities and resources. Review the local history of power failures and extreme weather events.

**Identify vulnerable members of the population**
(mobility issues, health problems, medications, health care providers, family/friends, etc.)

**Establish time threshold protocols for first responders**
(based on thermal resilience triage, as derived from thermal resilience analyses of buildings portfolio)
Example:
24 hours for evacuation of most vulnerable;
48 hours for transfer to place of refuge;
96 hours to remain in situ before re-visit/review.

**Ongoing monitoring and appropriate response**
(transfers and evacuations of inhabitants as required until power is restored - inspection of building services for pipe freezing, etc.)

**Thermal Resilience Triage**

- evacuation of most vulnerable individuals to elsewhere (medical assistance if required)
- temporary transfer of affected persons to place of refuge within facility
- persons allowed to remain within their dwelling units until power is restored

***Figure 1.*** *Framework of thermal resilience protocols and procedures.*

## RESULTS

All simulation results cannot be conveyed in this paper. However, an example of the work is presented in order to highlight some of the issues and challenges. Existing buildings may be most challenging because an often overwhelming number of issues need to be resolved to achieve an acceptable level of thermal resilience.

The Bois Ellen housing project in Montreal was selected among others to assess its thermal resilience. Figure 2 depicts Building A of the development and lists the relevant simulation parameters. It is important to note this building is more energy efficient than much of the older social housing stock in Montreal, but not as advanced as possible by imlementing best practices.

- 13 storey building constructed to Novoclimat + standard
- Exterior walls RSI 2.9 (R-16.6)
- Roof RSI 4.3 (R-24.6)
- Windows USI 1.6 (U-0.28), SHGC 0.6
- Infiltration 0.45 ach @50 Pa
- Thermal mass 200 mm (8 inches) concrete between floors
- No solar shading devices
- No natural ventilation

***Figure 2.*** *Bois Ellen Building A and simulation parameters.*

Beginning with cold weather passive habitability, Figure 3 indicates that approximately 45 hours after a power failure in winter, the temperature in north-facing suites falls below the lower passive habitability threshold of 15 $^{o}$C. Based on the thermal resilience triage in Figure 1, this time represents the period during which the most vulnerable occupants need to be evacuated, followed by the transfer of other affected persons to a place of refuge within the building. It will be much longer before periodic inspections of the building services are necessary (e.g., freezing of pipes, etc.).

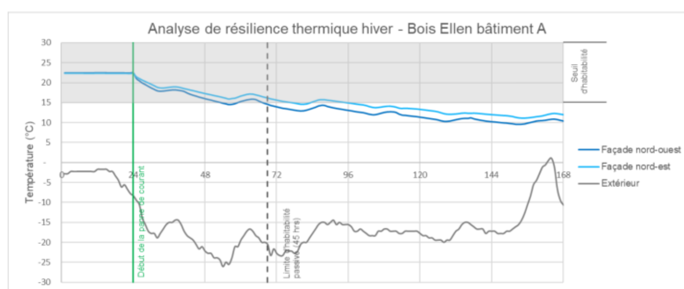


***Figure 3.*** *Bois Ellen cold weather passive habitability.*

One issue is whether or not most power outages will not exceed approximately 2 days duration. Another issue is providing a warming centre as a place of refuge within the building. Almost all older buildings were not designed with his consideration in mind and it may be both costly and difficult to incorporate such a facility within existing buildings. A combined heat and power plant running on a non-electricity energy source may be a feasible alternative, but not always possible.

Looking at the hot weather passive habitability in Figure 4, after about 10 hours the upper threshold of 30 ºC is exceeded for south-facing suites. Evidence indicates that more deaths and medical episodes are caused by over-exposure to heat than to cold, hence it is critical that much less time is afforded to first responders for evacuating the most vulnerable occupants during extreme hot weather power failures than cold weather events.

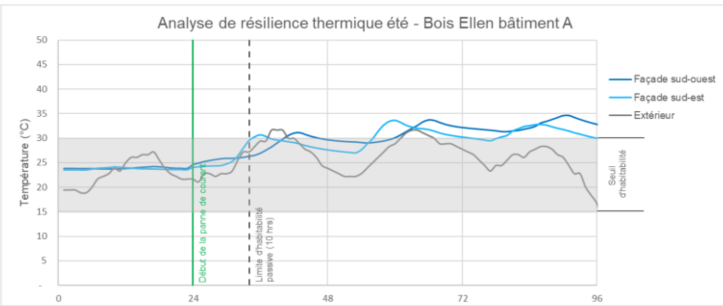


***Figure 4.*** *Bois Ellen hot weather passive habitability.*

Passive strategies for enhancing hot weather thermal resilience in buildings include:

- Control of heat conduction through opaque enclosure elements with higher effective levels of insulation;
- Control of infiltration through an effective air barrier;
- Control of solar gains through fenestration by selecting higher thermal efficiency glazing with a lower solar heat gain coefficient, and providing shading devices to block the sunlight; and
- Control of indoor temperatures by provision of thermal mass and natural ventilation.

Such passive strategies may be deployed in new buildings, but are often difficult to implement in existing buildings. The specific attributes of a particular jurisdiction's social housing stock must be considered when formulating policies, plans and protocols for enhanced thermal resilience. An inventory of first responder capabilities and the history of extended power outages for the locale must be examined. Feasible options are not always clear. For example, should a renewable energy system be provided to run fans for better air movement and ventilation in all suites? Should a back-up emergency generator be provided to operate a place of refuge (cooling centre)? Should there be one central place of refuge for the building or one per floor? It soon becomes obvious that solutions must respond to the particular context of the building and its microclimate. In some cases, no amount of passive measures will provide adequate cooling and it must be recognized that active cooling and uninterrupted power supply are essential services.

## RECOMMENDATIONS

The recommendations pertaining to new buildings are presented in Table 1 below. The process for dealing with existing buildings is still evolving and requires a great deal of measurement and verification to correlate simulation predictions with actual indoor conditions.

***Table 1.*** *Summary of recommendations to guide new social housing projects.*

| WHAT TO DO |
| --- |
| Minimal and Affordable Measures<br>• Minimize thermal bridging<br>• Increase effective levels of thermal insulation<br>• Manage increased potential for interstitial condensation<br>• Enhance envelope airtightness<br>• Assess the performance of each façade according to its solar orientation and construction typology (i.e., wood versus concrete)<br>• Provide clearer guidelines for indoor air quality and reduce/eliminate off-gassing due to interior materials, finishes, adhesives, sealants, paints, etc.<br>• Require energy simulations of thermal resilience starting at early stage of design<br>• Simplify mechanical systems – reallocate savings to enhanced building envelope<br>• Allocate funds for future measures to improve performance |
| Towards Passivhaus Measures |
| • Install sensors/probes in 10% of the suites to monitor performance/behaviour and inform post-occupancy evaluations<br>• Adopt airtightness standard of 0.6 ach @ 50 Pa (Passivhaus)<br>• Establish a minimum threshold of thermal autonomy<br>• Provide refuge areas for 10% of the area of each floor in the building<br>• Provide 50% of the energy supply from renewable sources on large scale projects<br>• Institute measures to conserve thermal mass to enhance passive habitability. |
| HOW TO DO IT |
| • Incorporate clear commitments from the general contractor in the contract estimate<br>• Require general contractors to satisfy a prequalification system during the tender stage<br>• Develop a Novoclimat training program for general contractors and their trades<br>• Require air tightness testing in a number of units, early in the construction<br>• Establish a commissioning period of 2-3 years; hire a third party; provide an appropriate budget<br>• Allocate a budget for the education and awareness of the inhabitants<br>• Ensure fees for professionals are adequate and reflect the level of effort needed for Novoclimat certification<br>• Provide post-construction energy performance monitoring and evaluation |

Within the context of Montreal's climate and the ambitions of Service de l'Habitation, Ville de Montréal, enhancing the thermal resilience of new building projects is straightforward and feasible to implement over time. Two big strategies emerge: 1) high-performance passive measures; and 2) better airtightness plus commissioning to realize the full potential of what has been designed and constructed.

## DISCUSSION

There remain a great many unknowns pertaining to thermal resilience design of buildings. They are always a function of the condition, attributes and occupancy of the building. For example, tall buildings housing very ill persons, without emergency power supplies for elevators, make it difficult to reach and evacuate mobility-challenged occupants on higher floors. In practical terms, this means more time must be allowed to evacuate the most vulnerable, and subsequently to move those adversely affected to places of refuge within the building. Establishing acceptable habitability time thresholds must account for the availability of first responder personnel and resources. Scenarios must also account for coincident crises, such as pandemics or fires, that reduce their availability.

It is also recognized that thermal resilience planning and design has not been formalized (Porritt et al., 2012). There is not yet a consensus about best simulation practices and procedures in terms of risk analysis (Sailor, 2014), and extreme weather data for simulation (Pernigotto et al., 2020 and Laouadi et al., 2020). A great deal of field work is is still needed to correlate predictions with actual outcomes.

Organizations that aspire to enhancing the thermal resilience of their building portfolios continue to lack formal methodologies of risk assessment and for the development of policies, protocols and procedures. Climate change has spurred interest in adaptation strategies to improve resilience but it is taking time for professional disciplines to craft appropriate responses.

It is hoped that advances in this field will come from proactive research and development reinforced by pilot demonsration programs rather than learning from losses and mistakes incurred while facing disasters.

## CONCLUSIONS

The process presented in this paper embodies a number of practical considerations and admittedly is neither technically comprehensive nor scientifically rigorous. The general approach to taking inventory, examining history, identifying risks and predicting habitability time thresholds accordingly, as advanced in this paper, has yielded helpful information and provided a way forward.

The resilient building design field requires further empirical study and practical application before it can reliably deliver acceptable health and safety through a suite of suitable passive measures and essential active back-up systems. It is also important to appreciate the roles and capabilities of social agencies and first responders as they relate to vulnerable populations.


## ACKNOWLEDGMENTS

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# SUPPORTING THE DEVELOPMENT OF NET-ZERO ENERGY READY BUILDING CODES

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## ABSTRACT

The Construction Research Centre of the National Research Council of Canada (NRC) is conducting research in support of the development of updated National Model Construction Codes. The research is directed at informing decision making for the National Energy Code for Buildings of Canada (NECB), and Section 9.36 of the National Building Code (NBC).

A review of international codes is presented, and the technical goal of 'net-zero energy ready' framed. Results of a simulation/cost study are presented to demonstrate that the goal is achievable. Remaining challenges are presented.

## INTRODUCTION

Globally there is a push towards improving energy performance of new buildings and existing building stocks. Examples include EPBD (Energy Performance of Buildings Directive) in Europe (BUILD UP, 2020) and in the US various versions of the IECC and ASHRAE 90.1 (US Department of Energy, 2020).

In the Canadian context the Federal, Provincial and Territorial governments' collective plan to address climate change is outlined in the Pan-Canadian Framework on Clean Growth and Climate Change (Canada 2016). The specific goals for the built environment are:

1. Making new buildings more energy efficient;
2. Retrofitting existing buildings, as well as fuel switching;
3. Improving energy efficiency for appliances and equipment;
4. Supporting building codes and energy efficiency in Indigenous communities.

Items one and two are being addressed via the national building codes and item one is the focus of this paper. National codes in Canada are developed by the Canadian Commission for Building and Fire Codes (CCBFC). Since 1937 the NRC has been developing and maintaining Canada's building codes and the CCBFC approves all changes proposed by any stakeholder. In 2016, the CCBFC published a position paper on the long-term development for energy codes (CCBFC 2016). This document outlines the policy positions on energy code development and introduces the concept of a Tiered-code approach to permit a flexible framework for adopting jurisdictions while also defining an 'ultimate performance target'. This is a significant change from current codes, where only minimum acceptable performance is defined. For new buildings the 'ultimate performance target' is defined as 'net-zero energy ready'. In addition to new buildings, CCBFC also recognises that the energy performance of existing buildings is a critical component to achieving national energy demand reductions; therefore, there is a need to develop technical guidance for improvements during alterations and renovations.

Energy provisions in Canadian codes are divided between the NECB and the NBC. The Standing Committee on Energy Efficiency (SC-EE) under the CCBFC is responsible for developing code change proposals for the NECB and NBC (specifically Division B, Section 9:36). The provisions in NBC 9:36 are only for housing and small buildings – essentially buildings types that are considered simple enough to not require professionals in their design (the technical definition is in Division A 1.3.3.3 (NRC 2015)). Every code change proposal is subject to a comprehensive review process including public review and final approval by CCBFC.

This paper highlights some of the technical challenges and achievements in converting policy directions into code language/technical requirements.

## REGULATORY CONTEXT

While the NECB and NBC are developed at the national level, they are modified and adopted by the Provinces and Territories, and then enforced (and sometimes further modified) by local authorities having jurisdictions, usually municipalities. This provides a challenge in developing harmonized codes, as individual jurisdictions can have vastly different drivers (environmental, economic, land availability etc.). This is particularly true in Canada, where energy resources vary across the country, and thus demands on energy efficient building codes differ. This is compounded by carbon accounting and general societal perspectives.

**International overview**

A review had been completed of approaches taken in other jurisdictions (Bourgeois, 2018). This review identified that energy code solutions were driven by the energy supply context of the adopting jurisdictions. In particular, the EPBD has many different implementations by EU member states.

The approach taken in France is notably different from other countries. Absolute targets for maximum energy consumption are defined as opposed to the more conventional reference vs proposed methodology, e.g., ASHRAE Standard 90.1 (ANSI/ASHRAE/IES 2019). Proponents of absolute targets argue that the method delivers real energy savings since the required performance is defined, as opposed to the conventional reference vs. proposed method where the target performance is defined relative to a notional reference building modelled using prescriptive rules. However, enforcement of a code with absolute targets requires a fully defined calculation procedure; in the reference vs. proposed method, identical assumptions made in both models can cancel out. For instance, infiltration rates in energy codes are often assumed; this is neutralized in the reference vs proposed method, as both buildings will be equally impacted. In the absolute method, the assumed rate will contribute directly to a pass/fail (note this is a separate issue from requiring airtightness testing and using a measured value). Likewise, assumptions related to occupancy, space use, etc. all directly affect the predicted performance. The solution in France was to develop a set of 'factors' that relax the headline energy performance target depending on space use, climate and altitude, essentially defining a reference building. The compliance target then ranges from 50 kWh/m$^2$ to over 600 kWh/m$^2$. This is particularly relevant for Canada due to the variations in climate across the country and the variations in building use/type covered by the NECB. Therefore, the current approach of reference vs. proposed is likely to be the most suitable method for performance assessment.

The review also highlighted the variation in scope and metrics used to assess energy performance. In some cases site energy is used (i.e., at the meter), in other cases source energy (i.e., at the power station) and in some cases energy is converted into equivalent carbon dioxide emissions. In the NECB and NBC, energy is regulated at the building, i.e., site energy. This is different from the goals of the Pan Canadian Framework, where carbon dioxide (and equivalent) reductions are the goal.

**Net-zero energy ready**

In their position paper, the CCBFC identified that Tiers of energy performance should be developed and that the top Tier should be 'net-zero energy ready'. The definition in the position paper is:

> *A **net-zero energy building** is defined as a high-performance building that combines superior standards in energy efficiency with renewable energy production to offset all of the building's annual energy consumption. A **net-zero energy ready building** is defined as a high-performance building that is built to the same level of energy efficiency as a net-zero energy building but does not include renewable energy production.*

It should be noted that the annual energy equation fails to identify peak load issues and potential temporal mismatches between renewable generation and demand (for example, see Clarke, Hensen, Johnstone and Macdonald (1999). Wide-scale deployment of renewables without concern of temporal effects has resulted in grid issues characterized by the 'duck' curve (Lazar 2016); essentially the rate at which utilities have to adjust their generation increases as PV goes offline in the evening while residential loads are increasing. This has results in a need for increased peak load capacity and grid stability management.

Recalling the definition of a net-zero energy building there is considerable latitude in defining the performance associated with a '*high* performance building' and '*superior* standards in energy efficiency'. Two studies were conducted to frame the ultimate performance goal:

1. How close are current code minimum buildings to net-zero energy ready performance levels?
2. What performance level are current net-zero energy buildings achieving?

To address the first question, existing building archetypes with renewable systems were simulated in several Canadian locations (Beausoleil-Morrison, Meister and Brown 2018). The work showed that single family housing in some locations could be considered net-zero energy ready when built to current codes. However, this required installing the maximum possible number of PV panels and thus would be cost prohibitive (cost is one of several considerations in determining code changes). For buildings the results were clear: additional energy efficiency measures are required. Therefore, for all building types, further improvements in energy efficiency are required before a building can be determined to be net-zero energy ready.

The second question was addressed by reviewing existing performance data. This data is sensitive to building type and limited information is available

(ASHRAE, AIA, IES, USGBC, & US-DOE, 2018, 2019). For small to medium offices and K-12 schools, the absolute energy performance varies by building type and location (see Table 1). It should be noted that these figures are for all energy consumed in a building – the NECB and NBC only regulate some energy uses, e.g., heating and cooling are regulated, but residential lighting is not. Thus, direct comparison is not possible, rather the figures should be used as a guideline.

***Table 1.*** *ASHRAE Design Guide Site Energy Targets ($kWh/m^2$).*

| ASHRAE Climate Zone | Small to Medium Offices EUI | K-12 School EUI |
|---|---|---|
| 4A | 69 | 60 |
| 4B | 65 | 58 |
| 4C | 55 | 56 |
| 5A | 73 | 60 |
| 5B | 72 | 60 |
| 5C | 55 | 56 |
| 6A | 87 | 65 |
| 6B | 78 | 62 |
| 7 | 96 | 68 |
| 8 | 114 | 75 |

## TIER DEVELOPMENT

Based on the constraints of current energy code as a minimum acceptable performance level and net-zero energy ready as highest performance level, the SC-EE proposed an additional two Tiers between these performance levels (i.e. four Tiers in total):

- Tier-1 is the enforced edition of the NECB;
- Tier-2 at least a 25% energy reduction from Tier-1;
- Tier-3 at least a 50% energy reduction from Tier-1;
- Tier-4 at least a 60% energy reduction from Tier-1.

To validate if the Tiers were technically possible and to determine cost impacts, a simulation study was undertaken on the following six archetypes:

- Secondary School (2 storeys, 19,600 $m^2$);
- Medium (3 storeys, 5,000 $m^2$) and Large (12 storeys, 46,300 $m^2$) Offices;
- Warehouse (1 storey, 4,800 $m^2$);
- Retail Strip Mall (1 storey, 2,100 $m^2$); and
- Highrise Apartment (10 storeys, 7,800 $m^2$).

Annual simulations of these archetypes were conducted for five locations: Victoria BC, Windsor ON, Montreal QC, Edmonton AB, and Yellowknife, NT, representing climate zones (CZ) 4 to 8. Both the base (NECB 2017) and Tier-compliant set of archetypes were simulated and the differences costed, totaling 120 simulations.

### Simulation Method

An engineering approach was applied to the simulations: the models were analyzed and the least performing aspect improved iteratively until Tier 4 performance was achieved. The solution arrived at via this 'hill climbing' approach demonstrates that the technical goal can be achieved (the primary objective of the analysis), but does not necessarily represent the cost-optimal solution.

Key energy performance areas examined include: additional insulation in opaque assemblies; reduced glazing area; increased window performance; alternative HVAC systems and heat recovery. Internal gains were also examined. Lighting technology can already deliver substantial savings over current code maximums and are expected to further improve (the expected high end value was used for Tier 4). Although plug loads are not currently regulated expectations are that office equipment will become more energy efficient, therefore reduced load assumptions were examined.

Some options available to practitioners were not examined: window distribution (all facades had equal glazing areas), orientation and form remained static for each archetype.

To manage the simulations the BTAP environment (authored by NRCan) for OpenStudio was used. This enables a consistent application of energy efficiency measures to the archetype models using EnergyPlus as the calculation engine.

### Tier-4 Sample Design Solution Set

All six archetypes in all five locations can achieve the Tier-4 target (and by extension the lower Tiers). Each solution was unique, and Table 2 presents an overview of the initial NECB 2017 and Tier 4 archetype descriptions for the Secondary School, Warehouse, Highrise Apt, and Retail Strip Mall. Complete results and data for Offices are available (Vuong, Barssoum, Macdonald and Wills 2019).

Incremental costs for the Tiers were estimated by a cost consultant. Note that these costs represent only the elements of the building that effect energy performance – for example it was assumed that structural costs would be identical in all cases for a specific archetype. Table 3 summarizes the incremental costs for Tier 4. In some cases the cost to build to the higher performance level is less than current code. This is primarily due to smaller window areas and smaller HVAC equipment resulting in cost savings offsetting increased insulation costs.

This analysis was cross-referenced with other studies. Simulated data showed little correlation between overall performance and cost. Therefore, these costs are subject to considerable variation depending on myriad design decisions.

***Table 2.*** *Tier-4 Description of Secondary School, Warehouse, Highrise Apt, and Retail Strip Mall in CZ-4 to CZ-8.*

| Component | NECB 2017 | Tier-4 |
|---|---|---|
| Wall R-value [(°F·ft2·h)/BTU] | R18 – R31 | R36 – R57 |
| Roof R-value [(°F·ft2·h)/BTU] | R30 – R47 | R40 – R57 |
| Window U-value [W/(m$^2$K)] | 2.1 – 1.4 | 1.2 – 0.7 |
| Window-Wall Ratio | 0.4 – 0.2 | 0.26 – 0.08 |
| Air Leakage [L/(sm$^2$) @ 75 Pa] | 1.45 | 0.2 – 0.8 |
| Shading | N/A | Horizontal (30% window length) |
| Air Handling Unit | MAU, RTU | Through Wall DOAS+ERV, VAV |
| Heating/Cooling | Baseboard, Boiler, DX Cooling | Baseboard (only in some), Condensing Boiler, DX Cooling |
| Service Hot Water | Electric/Gas Water Tank | Air Source Heat Pump (ASHPWH) |
| Lighting | NECB Table 4.2.1.6 | 70%-85% reduction |
| Electrical Equipment | NECB Table A-8.4.3.2.(1) and (2) | 70%-85% reduction |

***Table 3.*** *Tier-4 Archetype Incremental per Area Cost ($/m$^2$) for 5 Locations in Canada (CZ-4 to CZ-8).*

| Archetype | Victoria BC (CZ 4) | Windsor ON (CZ 5) | Montreal QC (CZ 6) | Edmonton AB (CZ 7a) | Yellowknife NT (CZ 8) |
|---|---|---|---|---|---|
| Secondary School | $44 | $59 | $58 | $58 | $32 |
| Medium Office | -$102 | -$150 | -$162 | -$174 | -$55 |
| Large Office | -$97 | -$91 | -$29 | -$52 | -$65 |
| Warehouse | $50 | $111 | $36 | $53 | $48 |
| Retail Strip Mall | $78 | $4 | $60 | $70 | -$7 |
| Highrise Apt | $57 | $37 | $11 | $36 | -$37 |

## DISCUSSION

For all Tiers increasing the insulation level for opaque assemblies proved less effective than reducing fenestration transmittance and area (higher performing windows can help offset the lower fenestration and door to wall ratios used). Increasing the insulation level for opaque assemblies results in diminishing rates of return on energy use reduction; although heat losses are reduced, additional cooling energy (fan, water pump) is required in many cases (typically those with large internal gains). It should be noted that thermal bridging in the envelope remains a concern and that improving airtightness was identified as the most cost effective route to achieving energy performance gains.

Although reduced lighting results in increased heating, for the majority of the locations this additional energy consumption is negligible when compared to the direct energy saved. As a result, for Tier-4, more efficient lighting technology must be used to deliver reductions in the range of 70% to 85% compared to current code. This will be a challenge for the lighting industry; indications from SC-EE members are that 50-60% are achievable with current technology.

It was found that HVAC changes, e.g., replacing constant volume (CAV) with variable volume (VAV) systems, adding dedicated outdoor air system (DOAS) and other HVAC changes greatly reduces the energy consumption of the archetypes. This is attributed to the inefficient CAV rooftop units and make-up air units currently prescribed in the baseline ('reference') NECB 2017 archetypes.

## CONCLUSIONS

Developing technically sound code requirements to deliver net-zero energy ready building performance requires a nuanced understanding of the drivers and goals. Reviews have shown that other jurisdictions have tailored their codes to their contexts. This presents challenges for a national code in a diverse country.

Work to frame the target has shown that a single EUI is not the most appropriate and that further improvements in energy efficiency are required to deliver 'net-zero energy ready' buildings. It has been demonstrated via simulation that these goals are achievable with minimal cost implications.

Future work is required to ensure the availability of solutions that deliver the assumed performance levels in the simulation study. In addition, the solution sets identified in the initial study should be expand and there is growing need to validate that the predicted savings at design are being achieved once the building is operating.

## ACKNOWLEDGEMENT

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# A NEW HOUSING STRESS TEST: CODIFYING THERMAL RESILIENCE OF BUILDINGS

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## ABSTRACT

With increasing frequency and severity of natural disasters and other events that cause power outages, combined with increasing reliance on building automation systems, incorporating thermal resilience into buildings is of critical concern. Given building codes often drive new building design, they should incorporate the best practices for resilient design. This paper describes a brief building simulation study with a house to demonstrate the effectiveness of various categories of resilience upgrades. Following that, possible pathways for incorporating thermal resilience into building codes are discussed.

## INTRODUCTION

With the progression of climate change, natural disaster-induced power outages are becoming more frequent and longer duration (Konisky, Hughes and Kaylor, 2016, Government of Canada, 2019). In the past several decades, Canada has experienced numerous widespread multi-day outages, such as those caused by ice storms in 1998 and 2013 (see **Figure 1**) and the power outage in summer 2003. To make matters worse, such outages are more likely to occur in periods of extreme cold (e.g. from ice storms) or extreme warmth (e.g., grid overload from air-conditioning) (Spengler, 2012). Given the reliance of heating and cooling to maintain acceptable indoor conditions in our buildings, power outages can pose a serious risk to buildings and their occupants. Accordingly, resilience to such outages is becoming recognized as a priority. While resilience is broad and can cover access to water, food, light, and clean air, this paper is focused on the thermal domain – including both the comfort and health of occupants and the temperature of buildings to avoid damage (e.g., frozen pipes).

In the past decade, several papers have begun to quantify thermal resilience of buildings using simulation to both quantify it and improve it. For example, Levitt, Ubbelohde, Loisos and Brown (2013) introduced the notion of thermal autonomy, which is defined as the fraction of the year that a building is comfortable for occupants without heating or cooling. O'Brien and Bennet (2016) applied passive survivability as a metric to quantify the time before a building becomes unlivable (considering elderly occupants, for example) and set 15 and 30°C as lower and upper limits. Since then, the metric was renamed passive habitability Ozkan, Kesik, Yilmaz and O'Brien (2019). Baniassadi and Sailor (2018) used a similar approach with small variations, such as using a discomfort index (mean of dry and wet-bulb temperature) at 28°C. More recently, Laouadi, Gaur, Lacasse, Bartko and Armstrong (2020) adapted the standard effective temperature (SET) to be more suitable for assessing comfort during heat waves: transient-SET (t-SET). A critical observation they made is that the appropriate upper threshold (for which they proposed 30°C) depends on whether occupants are acclimatized to warm conditions that occur during heatwaves.

*Figure 1. Example of a weather event that caused widespread long-term power outages (Toronto, 2013).*

In 2017, the USGBC introduced RELi Rating Guidelines for Resilience Design and Construction for assessing the resilience of buildings "against weather extremes, economic disruption and resource depletion" (United States Green Building Council, 2018). For residential buildings, it requires the indoor air temperature to remain above 10°C in the winter. In the summer, it must be demonstrated through models that the heat index never exceeds 32°C or that the wet-bulb globe temperature (WBGT) does not exceed 28°C. Heat index is a measure of air temperature that accounts for the fact that the human body's ability reject heat via evaporation is a function of relative humidity. WBGT is a weighted average of wet-bulb temperature (0.7) and globe thermometer temperature (0.3). RELi also prescribes availability of natural ventilation such that 2.36 L/s of outdoor air is provided per occupant with a windspeed of 0.5 m/s (specified as 118 $cm^2$ of opening for single-sided ventilation). In addition to passive survivability, RELi requires a source of back-up electricity (e.g., PV and battery storage) for at least four consecutive days.

While most reviewed studies have focused on using entire or parts of the typical meteorological year (TMY), e.g. (EPW, CWEC), Laouadi, Gaur, Lacasse, Bartko and Armstrong (2020) developed reference summer weather years (RSWY), which are built to represent more extreme heat waves from the past 31 years.

Ozkan, Kesik, Yilmaz and O'Brien (2019) assessed numerous MURB designs for three different climates and found a strong correlation between energy performance and resilience; many of the design qualities that benefit energy also benefit thermal resilience. O'Brien and Bennet (2016) quantified resilience for four different MURB designs (code-compliant and high-performance; with and without a balcony) and occupant types (passive and active). They found that both design and occupant behaviour can profoundly affect passive survivability in the winter by an order of magnitude from the worst to best case.

The existing literature is largely preliminary and with great diversity in methods to quantify and limit comfort, use of weather files, and discussion on possible methods to incorporate thermal resilience into the building code. Therefore, the objective of this paper is to provide possible methods to incorporate thermal resilience into the building code. The paper starts by presenting a brief simulation case study. Following the results of the case study, the paper discusses potential prescriptive and performance-based methods to codify thermal resilience of buildings.

## METHODOLOGY

To demonstrate the quantification of thermal resilience, a two-storey 10 by 10 by 5-meter detached house in Ottawa was modelled using EnergyPlus V9.0. The nominal design and variants are summarized in **Table 2**.**Error! Reference source not found.**The window to wall area ratio is assumed to be 20% on all sides of the house. The enclosure's effective thermal resistance values are outlined in the table. For modelling simplicity, the house is assumed to be raised above ground (i.e., floor is exposed to air). The combined mechanical ventilation and infiltration rate are assumed to be 0.5 ach in the base case. The nominal thermal mass is the inherent thermal mass in a light-framed home with an assumed effective thermal mass of furnishings, etc. The high thermal mass case includes a 15 cm masonry floor that is 10 by 10 meters (i.e., the entire floor)

Two types of occupants are considered: passive and active. The passive occupants do not actively attempt to adapt the house to improve thermal performance, whereas the active occupants adjust operable windows and window shades. When windows are open, the natural ventilation rate is assumed to be 10 $m^3/s$ based on engineering approximations considering the opening area and average wind speed.

A warm and cold week were selected from the 2016 EPW file for Ottawa, using the peak temperatures encountered in the house without heating or cooling, to assess resilience when the power is cut. These are summarized in **Table 1**.

Two types of resilience metrics were evaluated: time after power failure until the house reaches 5, 15 and 30°C and emergency energy supply required to maintain 21°C in the winter. The latter metric is the electric energy during the winter week required to provide lighting and operate a furnace fan (assuming a 90% efficient natural gas-fired furnace with an intact gas supply) or wood for a woodstove (assumed thermal efficiency of 80%). For the natural gas case, the PV area (assuming 18% efficiency, 45° slope) to supply electrical needs is calculated assuming a battery has at most a two-day capacity and it is fully charged at the time of power failure.

***Table 1.*** *Summary of weather data for resilience analysis periods in the Ottawa CWEC file.*

| | **WINTER** | **SUMMER** |
|---|---|---|
| **Date range** | Jan. 12-18 | Aug. 27-Sept. 2 |
| **Mean temperature** | -12.4°C | 21.3°C |
| **Mean of daily horizontal solar radiation peaks** | 273 $W/m^2$ | 760 $W/m^2$ |

## RESULTS

The results, summarized in **Table 2**, show that both building design and adaptive opportunities are critical to improving thermal resilience. The code minimum house performs particularly poorly and reached uninhabitable conditions (below 15°C) within three hours. The high mass case does not perform significantly better with regards to passive habitability (five hours). Deeper investigation revealed that, during the period without active heating, the heat transfer between the massive floor and indoor air and surfaces for small temperature differences is insufficient to adequately offset heat losses to the outdoors. Considering the significant thermal mass considered (15 cm concrete on floor), a possible approach to enhance thermal mass effectiveness is through active heat exchange (e.g., a fan or embedded pipe network).

The thermal mass, however, does significantly increase the amount of time before the house drops below 5°C – to over three days. The well-insulated house performed somewhat better regarding time till 15°C than the code minimum case, but not profoundly – in part because the code-minimum envelope is relatively good and because the overall heat loss remains quite high relative to the thermal energy storage. Notably, the combination of high mass and insulation allows the house to stay above 5°C – barely – for the entire winter week.

The active occupants effectively maintain the temperature below 30°C during the entire analysis period by using at least one of shading and operable windows. However, the thermally massive case also achieves this level of performance without requiring active participation of occupants. This result is important considering buildings that house occupants with disabilities or limited mobility. Overheating does not appear to be a serious concern in this case. A home with more south-facing windows would also be susceptible to overheating in the shoulder seasons when solar altitudes are low but temperatures are mild.

Unsurprisingly, the results showed that the high insulation case significantly reduced heating energy. This is particularly important for the back-up energy systems, which will be discussed next. The required PV array size to run lights and a furnace fan is between 1.0 and 1.6 kW (approximately 5 to 8 $m^2$ assuming 20% efficiency), with the high insulation cases yielding the lower end of the range. Alternatively, the amount of firewood (e.g. logs or pellets) required to maintain the house at 21°C was estimated considering the heating energy consumption during the winter week. As shown in **Table 2**, the values range between 193 and 324 kg of wood for the week. The calculations are based on Red oak – a hardwood with a heating value of approximately 15 MJ/kg.

***Table 2.*** *Model parameters and resilience performance.*

| | **CODE-MINIMUM (NBC-2015)** | **HIGH INSULATION** | **HIGH MASS** | **ACTIVE OCCUPANTS** | **ALL UPGRADES** |
|---|---|---|---|---|---|
| **Resilience parameters** | | | | | |
| Wall R-value ($m^2K/W$) | 3.08 (R-17.5) | 5.0 (R-28.4) | 3.08 | 3.08 | 5.0 |
| Roof R-value ($m^2K/W$) | 8.67 (R-49.1) | 8.67 | 8.67 | 8.67 | 8.67 |
| Floor R-value ($m^2K/W$) | 4.67 (R-26.5) | 6 (R-34.0) | 4.67 | 4.67 | 6 |
| Windows U-value ($W/m^2K$); SHGC | 1.60; 0.55 | 1.0; 0.4 | 1.60; 0.55 | 1.60; 0.55 | 1.0; 0.4 |
| Total effective ventilation + infiltration (ach) | 0.5 | 0.25 | 0.5 | 0.5 | 0.25 |
| Total UA-value (W/K) | 244 | 187 | 244 | 244 | 187 |
| Equivalent envelope R-value ($m^2K/W$) | 2.69 | 3.99 | 2.69 | 2.69 | 3.99 |
| Thermal mass | Nominal | Nominal | High | Nominal | High |
| Occupants | Passive | Passive | Passive | Active | Active |
| **Resilience performance** | | | | | |
| Winter: hours till 15°C | 3 | 8 | 5 | 3 | 19 |
| Winter: hours till 5°C | 34 | 80 | 78 | 34 | * |
| Summer: hours till 30°C | 63 | 65 | * | * | * |
| Electric energy for fan and lights (kWh) | 36.5 | 22 | 36.1 | 36.5 | 21.5 |
| PV array capacity (kW) for above electricity | 1.6 | 1.0 | 1.6 | 1.6 | 1.0 |
| Wood (kg) energy for heating to 21°C for winter week | 324 | 193 | 320 | 324 | 188 |

* Condition not reached during week

## DISCUSSION AND CONCLUSION

The results of this study show that thermal mass, a high-performance envelope, adaptive opportunities for occupants, a wood stove, and back-up power supply using PV can all increase the resilience of homes (and other buildings, by extension). In many cases, mutualistic relationships arise; for example, the well-insulated thermally massive house performed much better than the house with the individual upgrades.

Most building energy codes, including those in Canada, have a prescriptive and a performance path. For energy considerations, the prescriptive path sets building specifications (e.g. R-values, infiltration, HVAC) and the performance path specifies that the proposed design must use no more energy than a code-minimum reference building. The performance path necessarily requires simulation – usually on an annual basis.

In contrast to energy code requirements for which the relative annual energy performance is the focus, the absolute performance of homes under power outage scenarios is critical. While we cannot be sure about the trajectory of weather following a power outage event or the vulnerability of a home's occupants, the code should necessitate a degree of certainty that it can protect those occupants. Economics and environmental impacts aside, the consequences of a building using more energy than planned are relatively less critical than endangering the wellbeing of occupants – and in some cases the building (e.g., widespread flooding from frozen pipes). Accordingly, we recommend a simulation-based approach to the code but with absolute limits in temperature or overheating/underheating duration.

The selected requirements must incorporate typical extreme power outage durations, safety, and practicality (i.e., risk and rewards). In the case of building envelope, improved energy efficiency generally means improved thermal resilience. However, the other explored aspects are not yet requirements of Canadian building codes. As for all building code amendments, all aspects must be considered, including practicality, economics, enforceability, ease of implementation, etc. These aspects are beyond the scope of this paper.

It is notable that NECB specifies that occupants cannot be relied upon to improve energy performance. If such language were applied for resilience-related requirements, it would effectively not credit measures for adaptive opportunities (e.g., operable windows, shading). In contrast, the current study and literature (e.g., O'Brien and Bennet, 2016) demonstrates the value of adaptive opportunities. Moreover, NECB primarily credits energy savings from automated systems (e.g., occupancy-based lighting), whereas such systems may not function at all (and may be detrimental to performance) under power outage scenarios. We believe, in contrast, that adaptive opportunities should be rewarded and that manual overrides for systems (e.g. lighting, blinds, operable windows) should be mandated. RELi only covers one adaptive opportunity explicitly – operable windows— and does not thoroughly explain how they are used in simulation. RELi specifies that window openings must be large enough to provide 2.36 L/s of outdoor air (approximately that required by ASHRAE Standard 62) for windspeed of 0.5 m/s. However, this is wholly inadequate for natural ventilation for cooling effects. For example, if conditions are 5°C cooler outdoors than in, this ventilation rate only removes an order of magnitude less heat than is generated by occupants, let alone solar gains and other internal gains.

For the prescriptive path, the code should require a suite of passive and active measures. As shown in this paper, to a large extent the passive measures are consistent with improvements in energy efficiency (e.g., insulation, airtightness, window performance). Thermal resilience in the winter season can generally be considered the most challenging in most Canadian climates. A back-up heat source (e.g., wood stove) combined with a high-performance envelope are critical. As demonstrated by the current case study, a high-performance envelope is not sufficient for multi-day power outages.

In the future and particularly in urban environments, a growing threat to thermal resilience in the summer is that overnight temperatures can remain warm. In the current case study, the summer week that was used to evaluate resilience had temperatures that dropped to 15 to 20°C at night. Such conditions, coupled with strategic night-time ventilation and structural thermal mass can greatly reduce daytime overheating. However, if temperatures remain warm (e.g. mid-20s °C) at night, there is significantly greater risk of overheating.

A design feature that was not explored in the current simulation study is inclusion of a "safe room" that can be conditioned with relatively less energy to comfortable temperatures using back-up energy sources even if the main energy supply is cut. To some extent, even a basement could serve this purpose to escape summer heat. The current study did not involve a basement.

Beyond architectural design features, a valuable feature to improve thermal resilience is a manual drain valve that allows supply (i.e., pressurized) pipes to all be drained in the even that the home needs to be evacuated in the winter.

A gap in knowledge in the literature is a consistent metric for assessing thermal comfort and survivability – both in terms of the formulation of the metric and the threshold value. As noted by Laouadi, Gaur, Lacasse, Bartko and Armstrong (2020) occupants who are acclimatized to warm conditions are more likely to cope during a power failure. Accordingly, perhaps codes should mandate that air-conditioned buildings should use lower thresholds than their naturally-ventilated counterparts. Homes without air-conditioning are more likely to have ceiling fans, cross-ventilation, etc.

An area requiring future work is to systematically identify the periods of the year that are used to assess resilience. Two main complications arise: 1) the typical meteorological year (TMY) data is specifically designed to be average and not extreme or based on cliamte change, and 2) the pain point of buildings (e.g., high solar intensity, solar geometry, wind, extreme temperatures) and building design-dependent and cannot necessarily be generalized. In the example above, the house was very vulnerable to intense solar radiation and low solar altitudes – until shading was deployed. In contrast RELi specifies the extreme weeks by dry-bulb outdoor air temperature only.

Two further areas for future fundamental research include: 1) quantifying the ability of occupants to adapt and optimally use adaptive opportunities (e.g., predictively with nighttime ventilation), 2) quantifying reasonable comfort limits as a function of history and acclimitization. Both could be incorporated into simulation-based code requirements for resilience.

## ACKNOWLEDGMENT

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# LESSONS LEARNED WITH RESPECT TO THE CAE ROADMAP FROM THE MONITORING OF A HIGH-PERFORMANCE SOCIAL HOUSING BUILDING IN QUEBEC CITY

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## ABSTRACT

A prototype was built in Quebec City to demonstrate the feasability of low-energy social housing buildings. The case study building was heavily monitored to follow its energy performance. This paper presents observations that emerged from this project regarding the design and operation of this social housing building. It shows the energy consumption of each individual dwelling, the indoor temperature in summer and heat fluxes flowing through the envelope. Lessons learned regarding low-energy residential buildings that are resilient and powered by renewable energy are discussed.

## INTRODUCTION

The residential sector consumes ~20 % of the energy in Quebec and is largely responsible for electricity peak demands. Improving the design and operation of dwellings can offer opportunities for reducing the energy demand and providing flexibility in terms of load management. There are currently more than 3.5 million households in Quebec, 38.6% of which are tenants. Of this number, more than 225,000 households have benefited from at least one of the programs of the *Société d'habitation du Québec* (SHQ), the governmental organization supporting access to affordable dwellings. The social housing building stock is thus quite large and plays a critical role for many low-income families. Improving the energy performance in social housing buildings can reduce their operational costs and environmental impact. It can also increase the well-being of vulnerable populations (Vellei et al., 2017).

Recent studies on energy-related aspects of Canadian social housing have focused on indoor air quality (Akom et al., 2018), retrofitting (Tsenkova, 2018), energy monitoring (Rouleau et al., 2018) and policies. In the context of the CAE roadmap, many questions and challenges remain for achieving low-energy social housing, that is higly resilient and powered by renewable energy. With the emergence of the concept of energy justice (Jenkins et al., 2016), these challenges are becoming more and more acute.

In 2015, a new social housing building was erected in Quebec City. The stakeholders decided to aim for a low energy building. Additionally, this project was used to test and document different options (with the idea to replicate successful elements in future projects) and more generally, to study the energy performance in this kind of building. In the next sections, we present the main features of the building. Then, we share some of the main takeaways of our study regarding the building energy performance, its resiliency to heat waves and the performance of its low-carbon envelope.

## PRESENTATION OF THE CASE STUDY BUILDING

### Architectural features

The building has four storeys and a total of 40 dwellings (Figure 1). The floor surface area of each unit varies from 70 to 80 m$^2$. The building is oriented in the 49° direction and the window to wall ratio (WWR) is 16.0%.

Achieving a low-carbon design motivated the use of wood for the structure and envelope of the building. An interesting feature of the building is that one side was constructed with a cross-laminated timber (CLT) system, and the other side, with a light-frame system. This allowed for a direct comparison of the costs, construction processes, and heat and mass transfer features of both constructive systems. The RSI value of the opaque portion of the envelope is 6.32 for both construction systems. The tightness of the enveloppe was measured to be 0.6 ACPH at 50 Pa.

### HVAC&R features

The building is part of a "green neighborhood" equiped with a district heating system. Centralized wood pellet boilers deliver water around 80°C to the neighborhood, including to the case study building. Wood pellets can be seen as an alternative renewable energy source and offer an outlet for the byproducts of the wood industry (Padilla-Rivera et al., 2017). Within the building, each appartment is equiped with 3 to 4 hot water radiators.

***Figure 1.*** *Picture of the case study building.*

The building has no mechanical cooling. Therefore, occupants rely on window opening to control the indoor temperature in the summer. Although some windows are shaded by the balconies of the upper dwelling, most windows have no shading systems, except for interior blinds. The southwest façade is also partially shaded in summer by trees. A 100% centralized fresh air ventilation strategy is used, with a heat recovery system. Each household has acccess to an on/off switch to control the mechanical ventilation in its dwelling. A solar wall allows to preheat makeup air when it is advantageous. Domestic hot water is heated by the district heating network. A recirculation loop within the building ensures a fast DHW delivery to occupants.

**Monitoring**

Temperature and humidity, consumption of domestic hot water, space-heating and electricity, window opening, and use of mechanical ventilation were measured in different dwellings every 10 minutes. Additionnally, temperature, humidity and heat flux sensors were installed in the envelope. More than 350 sensors have been used. Data has been collected since october 2015.

## ENERGY PERFORMANCE

Figure 2 presents a summary of the energy concumption in 2018 for each dwelling and per energy budget items. An interesting conclusion that arose from the study is the importance of the domestic hot water (DHW) load in the building energy balance. As efforts are devoted to improving building envelopes, the space-heating demand can be significantly cut down. In the present building, space-heating requires 33.3 kWh/m$^2$y on average, which is signifiantly lower than the average value of the residential sector. As a result, the share of energy required for the other loads become dominant and the “next” critical load to focus on to reduce energy consumption is DHW. Note however that because of the recirculation loop, a part of the energy used for DHW contributes to the heating of the building. We estimated that 10 to 15 kWh/m$^2$ of the energy consumed by the DHW system could contribute to space heating. By predicting in advance the DHW demand, it is possible to adjust some features of the system in order to minimize energy consumption or move DHW production to off-peak periods (Maltais LG and Gosselin, 2019).

One of the most striking take-aways from Fig. 2 is the large variability of energy consumption between the different dwellings. Only a very weak correlation of the DHW consumption with the number of occupants in the dwellings and of the space-heating demand with respect to the floor level were noted, but other factors such as orientation, constructive system, etc., were not able to explain the variance of the energy intensity. Most of the observed variance was due to the occupants themselves. In other words, buildings can only be as energy efficient as the people that use them. This emphasizes the need for building designs to be as robust as possible in front of the wide variations of possible occupant behaviors, as far as a low energy intensity is desired.

The so-called “energy performance gap” was also investigated, i.e. the difference between the preconstruction energy simulations and the actual energy consumption. The prior-to-construction estimation of the energy consumption is shown in Fig. 2 (PHPP). The difference between this prediction and the actual consumption is significant, but in line with those reported in literature. Rouleau et al. (2018) identified the assumptions of the original model that did not concur with actual observations. Among the most influential factors that were not well captured by preconstruction models are the set-point temperature, the use of windows, which were assumed constantly closed for preconstruction forecasts, but in reality were open on average 9.4% of the time (more than two hours per day) during winter.

## RESILIENCY TO HEAT WAVES

As mentioned above, there is no mechanical cooling in the building. Different studies have pointed out the threat posed by heat waves, in particular for vulnerable populations, a problem that becomes more acute as climate changes increase their occurence.

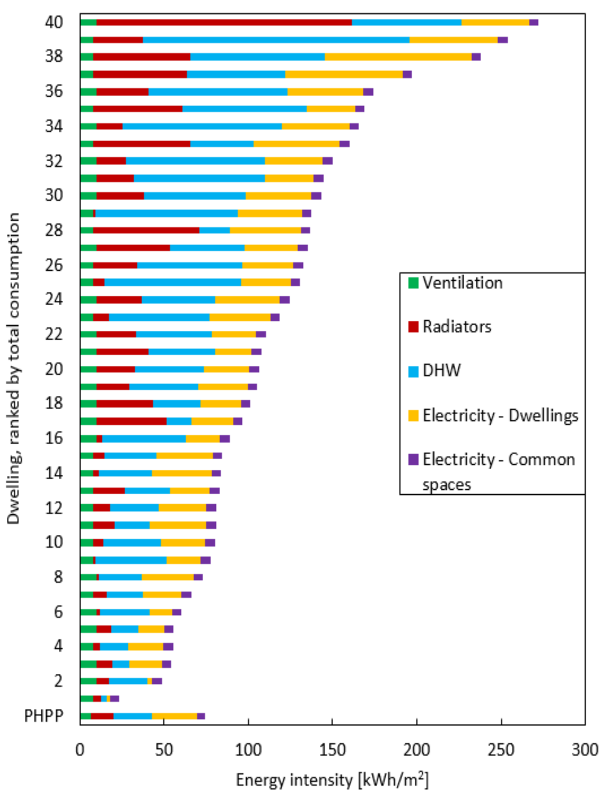


***Figure 2.*** *Specific annual energy intensity of all dwellings in 2018.*

Based on temperature measurements and adaptive comfort model, it was determined that several dwellings experienced overheating during summer. From June to September 2018, the time spent outside the comfort zone varied between 5.0% and 70.9% depending on the unit. The large difference between these values shows that occupants not only have a large impact on energy consumption, but also on thermal comfort. Fig. 3 shows the indoor temperature for the coldest and warmest dwellings during the summer. Black lines represent the limit of acceptable thermal comfort according to ASHRAE 55. The prevailing mean outdoor temperature is the exponentially-weighted running mean temperature of the last month.

The data seemed to indicate that the dwellings in the CLT portion of the building were more prone to overheating than those in the light-frame portion. However, our study showed that overheating was due to a good extent to occupant behaviors (e.g., actions on windows, blinds, mechanical ventilation, etc.) which vary greatly from one dwelling to another. Statistical tests and simulations were not able to confirm the impact of the wall assembly on overheating.

From the beginning of June to the end of August, it was warmer inside the dwellings than outside 90.2% of the time. This figure combined with the high frequency of overheating suggests that heat generated by passive solar gains and electrical appliances is trapped in the building. The high level of insulation of the envelope is unhelpful from that standpoint. It appears necessary to develop heat extraction strategies (increasing mechanical ventilation rates, ensuring that ventilation on the dwelling scale is activated and that radiators are turned off…) to mitigate overheating risks in summer in low-energy social housing buildings. Preventing non-necessary heat gains by adding exterior shading devices

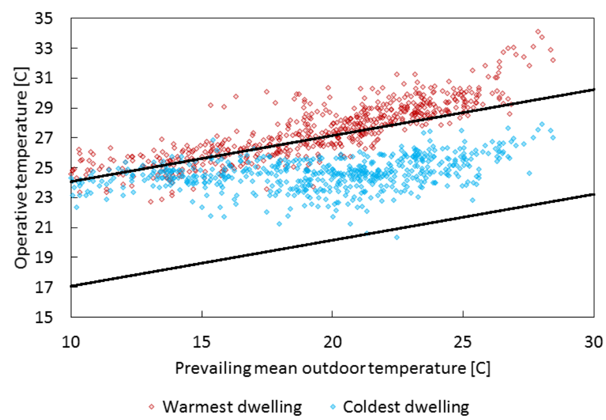


***Figure 3.*** *Comparison between the indoor temperature and the acceptable range prescribed by ASHRAE Standard 55 for the coldest and warmest dwelling.*

or minimizing heat losses from the recirculation loop would also be beneficial.

## LOW CARBON ENVELOPE

As building designs are more and more energy efficient and as renewable energy sources are more deeply integrated at the building scale, embodied carbon related to building materials is gaining importance in the consideration of buildings' global warming potential (GWP) from a life-cycle perspective.

Different life cycle analyses were performed to analyze the case study building. Even if the building was to be heated with natural gas, it was found that the impact of materials on the GWP of the building would still be slightly above 10% of the total GWP (Breton, 2019). Using greener energy sources (e.g., solar, geothermal, biomass, etc.) will only increase this percentage and put more emphasize on the impact of materials.

As mentioned above, the temperature, heat fluxes and humidity in the building envelope were monitored over an extended period of time. This allowed the hygrothermal transfers in the two envelope systems (CLT vs. light-frame) to be studied. Although the two types of envelope have the same R-value, they have

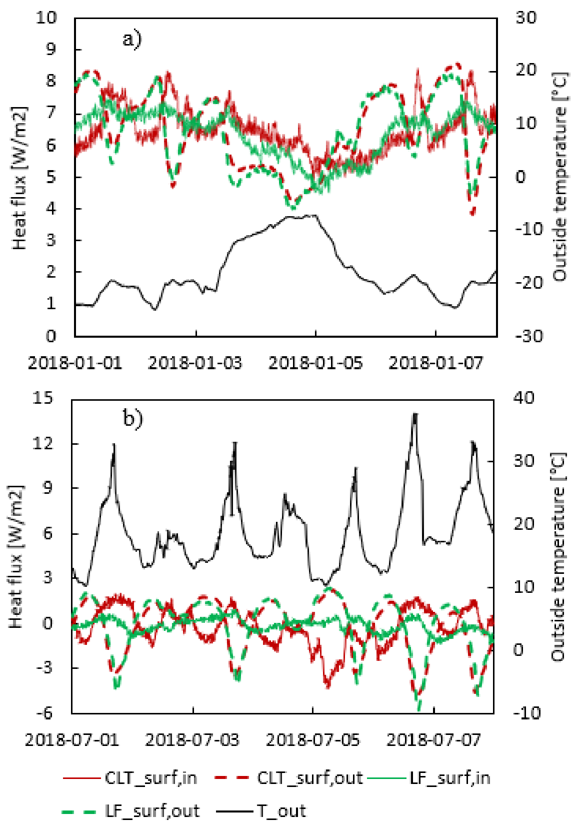


***Figure 4.*** *a) Winter and b) Summer comparison of the heat fluxes through the CLT and light frame envelope.*

significantly different thermal mass. Fig. 4 presents the heat fluxes flowing through the northeast façade of both types of envelope for one week in winter and one week in summer. The "outside" heat flux sensor is installed behind the brick façade whereas the "inside" sensor is behind the gypsum surface. The outdoor temperature is also shown. We observe that even during extreme weather conditions (-20 or 35°C), there were no large spikes of heat leaving (or entering) the building – heat losses remain relatively constant throughout the week. In Fig. 4b, when the outdoor temperature briefly reaches a maximal value of 37°C, the heat flux through the outside surface of both envelope systems was approximately -6 $W/m^2$. The negative value conveys that the heat is flowing towards the indoor environment, which is undesired in summer. However, at the same time, the heat flux on the inside surface of the same envelopes are 1.2 $W/m^2$ for the CLT system and 0.1 $W/m^2$ for the light frame wall, meaning that the dwellings are actually losing heat.

Sensors in the two envelope systems exhibit similar behavior, suggesting that the increased thermal inertia of the CLT system had no tangible effect on the thermal behavior of the envelope.

## CONCLUSION

This paper presented some key lessons learned from the monitoring of a Canadian social housing building that was designed to energy efficient. Heating for space heating and domestic hot water comes from wood pellet boilers and Hydro-Quebec provides electricity. Therefore, all the energy consumption of the case study building comes from renewables. The monitoring highlighted that the feasability of reaching low-energy targets greatly depends on occupant behavior. There was a high variability of energy consumption between all dwellings, primarily caused by the actions of the occupants (window openings, use of DHW, set point temperatures…). The first lessons would thus be to aim for robust energy designs that work well with a wide variety of occupant behaviors. The second lesson learned is that as building professionnals find solutions to reduce space-heating in dwellings, the share of energy required for DHW drastically increases. Research should attempt to identify strategies or technologies that cut down the energy required for DHW.

Variations among dwellings are also observed for overheating in summer. High insulation levels needed to achieve low-energy buildings are disadvantageous in summer since they prevent heat from escaping the indoor environment. The third main lesson of the paper is to keep in mind the required resiliency of low-energy building to heat waves.

The final lesson learned is that intrisic energy of material is becoming more important. With that respect, different wood enveloppe systems can offer both a low embodied energy and a high operational performance.

## ACKNOWLEDGMENT

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# AIR PURIFICATION TECHNOLOGIES FOR RESILIENT BUILDINGS: ABILITIES AND LIMITATIONS

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## ABSTRACT

Various air cleaning technologies are applied for chemical contaminants (CCs) removal in commercial air cleaners. These devices, if they work properly, can play a significant role in reducing building energy consumption, and removing CCs, hence improving the well-being of occupants and building energy efficiency. For removing CCs, the use of traditional adsorption-based air cleaning systems such as activated carbon requires quality maintenance and regular media changes. New electronic air cleaning technologies, such as photocatalytic oxidation and non-thermal plasma, are now available for general ventilation systems. Such technologies can be more energy efficient and may require less maintenance; however, their performance is less studied and less documented. This paper discusses the potential and the limitations of air cleaning technologies for the improvement of indoor air quality in resilient buildings.

## INTRODUCTION

Many of the materials used in construction and production of buildings material and buildings maintenance and operation as well as occupants' metabolism and use of consumer products can be sources of Volatile Organic Compounds (VOCs) in built environment. More than 300 VOCs have been identified in indoor air environment (ASHRAE, 2017). Even though VOC concentrations are relatively low in non-industrial environments, the high potential for many VOCs' presence in indoor air to cause symptoms is a result of both additive and synergistic effects. Due to the high volatility, VOC can easily vaporize under ambient conditions and inhalation is a major route of exposure. The potential harmful health effects of VOCs are irritations of upper respiratory system, eye and skin, sinus infection, allergic reaction, asthma, headache, fatigue, poor concentration, nausea, dizziness, and cancer. The indoor VOC concentrations are mostly higher than the ambient outdoors (ASHRAE, 2017). A field study of VOC levels in both indoor and outdoor air of office buildings in Montreal has shown that indoor total VOC (TVOC) levels are 2 to 4 times higher than outdoor, and according to LEED BD+C V4.1, TVOC limit is 500 ug/m^3 (Lee et al., 2009).

Ventilation is the generally adopted engineered solution to control the concentrations of chemicals in the air. The quantity of the outdoor air brought into the building can have a direct effect on the energy cost of building operations. There is a cost to heat, cool, humidify or dehumidify the outdoor air depending on the location and the season. This leads to a balancing act between occupants' health and ventilation cost. In the past decades, energy efficient building design and operation as well as the applications of renewable energy sources have been the prime objectives in building industry.

## AIR CLEANING TECHNOLOGIES FOR VOC REMOVAL

### Adsorption-Based Technologies

The traditional systems for filtering gases and vapors are based on adsorption process, i.e., activated carbon and/or potassium permanganate alumina pellets in trays or deep beds, particulate filters incorporating very thin beds of activated carbon or alumina pellets, and carbon cloth (Bastani et al., 2010, Haghighat et al., 2008). These adsorption-based technologies have long been used in wide ranges of applications, so their mechanisms and factors affecting the performance are relatively well understood. Properly designed adsoption-based air cleaning systems can have high efficiency. Currently available standards for the evaluation of gas-phase air cleaning devices were developed based on the behaviour of adsorption-based technologies (ASHRAE 2015 and 2016).

Main challenges in successful applications of adsorption-based air cleaning for IAQ improvement arise from the fact that hundreds of air pollutants exist in indoor air environment at various levels. The removal efficiency highly depends on the physicochemical properties of air pollutants and the media type (Khazraei et al., 2014). When activated carbons, which are most commonly used adsorption media for IAQ applications, are challenged with a mixture of different VOCs, weakly adsorbed compounds get displaced by those with stonger affinity, as shown in Figure 1 (Kholafaei et al., 2010). However, only single challenge gas testing is generally required in current standards (ASHRAE, 2015 & 2016).

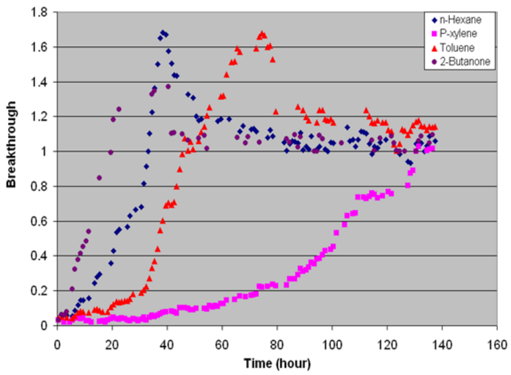


***Figure 1.*** *Displacement phenomena: 4 VOC mixture (5 ppm each) testing using 5cm bed of coal-based AC at 0.5 m/s air velocity (from Kholafaei et al., 2010).*

Since adsorbent media have limited capacitiy, regular media replacement is necessary. Therefore, predicting the service life of adsorbent-based air cleaner is important. Existing empirical or theoretical models have been developed and validated for industrial process applications or cartridges used in personal protection, where the number of challenge compounds is limited to a few and the challenge concentrations are relatively constant. Modeling IAQ application conditions is cumbersome considering the presence of numerous air pollutants and temporal changes of their levels, which resulted in limited researches.

With the fast advance of low-cost sensor technologies, air cleaning industry starts adopting gas sensors to indicate the time to change adsorbent media. However, the main concern is the lack of information on low-cost sensors' performance and limitations. Studies showed that these sensors are generally vulnerable to the changes in environmental conditions, chemical interferences and aging (McKercher et al., 2017). The validity of these sensor applications needs further investigation.

**Electronic Air Cleaning Technologies**

There are newer technologies so called electronic air cleaning (EAC) technologies such as ultraviolet irradiation (UV), UV with photocatalysts, plasma, plasma with catalysts, and ozone generators. The EAC technologies generate oxidizing agents like radicals and ozone, and removing the gases and vapors through oxidation process (Lee et al., 2017 & 2020; Zhong et al., 2013). Compared to the adsorption-based air cleaning systems, EAC systems are generally easier to maintain and have lower flow resistance resulting in the savings from the reduced fan sizes in air-handling systems. With these merits, EAC devices are quickly penetrating the market. Many studies have been conducted to develop better EAC systems, especially for photocatalysts (Mamaghani, et al., 2020; Shayegan et al., 2019), and demonstrated high removal efficiencies.

Air cleaners using EAC are often advertised that they can convert gaseous pollutants into carbon dioxide and water. This can be true if the challenge VOCs are hydrocarbons and completely oxidized. However, these results were often obtained under ideal oxidation conditions (e.g., long residence time under extremely high oxidizing agent output). Also, many studies used static batch test methods of which results are difficult to translate into dynamic performance of the in-duct systems that can be used in combination with ventilation.

For successful applications of these EAC technologies, air cleaning system should be designed and operated to ensure sufficient reaction. The performance of EAC significantly affected by air velocity, challenge VOC type and concentration and environmental conditions like humidity. Compared to adsorption-based technologies, the single-pass efficiency of EAC is generally lower and significant reduction is observed at higher challenge concentration as shown in Figure 2. The tested compounds are common VOCs found in indoor air so these are listed compounds in ASHRAE Std. 145.2 testing for gas-phase air cleaners.

Adsorbents, as shown in Fig. 1, in initial phase can have high efficiencies. Of course some thin bed of adsorbent or combination type filters can have lower efficiencies.

Complete oxidation is hard to achieve in actual EAC applications. In such cases, EAC can generate various intermediates including CO, formaldehyde, acetaldehyde, acetone and acetic acid along with some pollutants like ozone and nitrogen oxides inherently generated depending on the technology used (Mamaghani, et al., 2018; Shayegan, et al., 2017; Bahri and Haghighat, 2014). Due to the potential for the generation of these highly toxic by-products, the use of oxidation-based air cleaning devices needs to be carefully examined to prevent unexpected exposure. To address the by-product issue of EAC, some manufacturers include adsorbent media at the downstream of EAC unit; however, there is still lack of study on the performance of these scrubbers.

As more air cleaning devices using EAC technologies enter the market, it would be essential to develop a proper evaluation method for comparing their effectiveness and overall performances. However, there is no standard test method that can properly evaluate EAC technologies. Using the standards developed for adsorption-based technologies may cause problems as they accelerate testing by increasing the challenge concentrations and do not require any by-product measurements. Table 1 summarizes the air cleaning technologies discussed above.

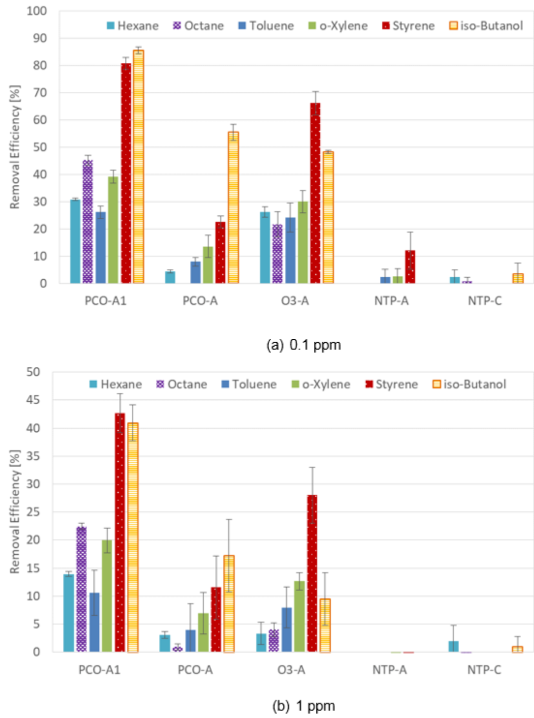


***Figure 2.*** *VOC removal single-pass efficiency of EAC at 0.5 m/s air velocity (Lee et al., 2020).*

***Table 1.*** *Summary of air cleaning technologies.*

| Adsorption-based technologies | Electronic air cleaning technologies |
|---|---|
| • Activated carbons<br>• Impregnated activated carbons<br>• Permanganate alumina<br>• Zeolites | • UV-PCO (Photocatalytic Oxidation)<br>• Plasma/Ion generators<br>• Plasma-Catalysts<br>• Ozone generators |
| • Higher pressure drop<br>• Regular media change-out<br>• Standard test methods exist<br>• Well-documented performances | • Compact / Lower pressure drop<br>• Easier maintenance<br>• No/limited standard test methods exist<br>• Uncertainty in performances<br>• Byproduct generation |

**Standards relevant to the applications of air cleaning systems**

ASHRAE Standard 62.1 (2019) specifies the requirements of ventilation system design and there are three design approaches: ventilation rate procedure (VRP), indoor air quality procedure (IAQP) and natural ventilation procedure. The mechanical ventilation system should be designed through the VRP and/or the IAQP.

The VRP is a prescriptive ventilation design approach that sets the minimum requirement for outdoor air ventilation rate for various space types. In the VRP, the outdoor air ventilation rate of a space is generally determined by simply adding the occupant-related demand and the building-related demand from the tabulated data. In VRP, improving IAQ is achieved by only dilution ventilation; therefore, having good outdoor air quality is necessary. Where poor air quality is expected, air cleaning has to applied; however it specifies only ozone removal with minimum 40% efficiency among gaseous air contaminants. This may pose challenges in ensuring acceptable IAQ in the era of climate crisis, since climate change is expected to cause deterioration of ambient air quality due to increased frequency and severity of air pollution episodes as well wild land fires.

The IAQP is a performance-based ventilation design procedure requiring explicit contaminant load calculation and engineering analysis to meet the contaminant limits. While the VRP accounts for only dilution ventilation for indoor air quality control, the IAQP allows implementing all contaminant control methods: source control, dilution ventilation and air cleaning. Use of proper air cleaning systems can reduce the required outdoor air ventilation rate. In spite of great potential for improved indoor air quality and energy saving (Johnson, 2005), the IAQP has not been widely applied. Lack of proper standards to evaluate the effectiveness of air cleaning systems, especially for gaseous contaminants, may be part of the reason , along with the lack of IAQ regulations and the significantly more decision-making required for the engineers when using IAQP (Stanke, 2012).

The need for the development of standard testing method for gas-phase air cleaning systems has long been discussed. ASHRAE has developed two laboratory test standards:

ANSI/ASHRAE Standard 145.1-2015 Laboratory Test Method for Assessing the Performance of Gas-Phase Air Cleaning Systems: Loose Granular Media; and

ANSI/ASHRAE Standard 145.2-2016 Laboratory Test Method for Assessing the Performance of Gas-Phase Air Cleaning Systems: Air Cleaning Devices.

These standards, however, clearly limited to traditional air cleaning systems using sorptive media. Standard development to include EAC technologies is under progress by ASHRAE Standard Committee, SSPC 145.

## CONCLUSION

A resilient building should be able to provide at least acceptable indoor air quality even under extreme situations. Relying on conventional dilution ventilation combined with particulate filtration may not be sufficient, Gas-phase air cleaning needs to be considered. Among gase-phase air cleaning technologies, the performances of traditional adsorption-based technologies are well studied and documented; however, newer EAC technologies have not been sufficiently investigated. This lack of thorough understanding of the performances of new technologies hinders the development of proper test procedures. At present, there are no test standards that can be applied for in-duct air cleaning systems using EAC technologies. As a result, design engineers only have data from testing done by manufacturers. Since each manufacturer develops its own test procedures, it is not possible to compare the performances of air cleaning products by different manufacturers. Also essential information like by-product generation is not reported. This lack of standards and convincing proof of actual performance greatly limits the proper use of EAC air cleaning systems.

## ACKNOWLEDGMENT

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# PATHWAYS FOR NET ZERO ENERGY BUILDINGS AND COMMUNITIES RESEARCH ACTIVITIES AT CANMETENERGY-OTTAWA

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## ABSTRACT

CanmetENERGY-Ottawa is developing a suite of projects whose objective is the improvements in retrofitting existing buildings, the design for new ones and their integration into communities that are able to deliver impacts on emission reduction targets. This paper provides the motivation for the work, outlines the activities and provides references for those interested in having more detailed information.

## INTRODUCTION

The primary motivation for research in buildings and communities at CanmetENERGY-Ottawa (CE-O) stems from the commitment of the Federal Government to reduce Green House Gases (GHG) to 30% by 2030 (Environment and Climate Change Canada, 2016) . In order to reach this target, residential and commercial building contributions will need to come from changes in the way these buildings provide the services Canadians rely on. These changes have implications on how we heat, cool and manage the electricity necessary for lighting and appliances, as well as how energy required for these services is managed at the community level.

The possible interventions in the building sector are constrained by a number of pre-existing conditions:

- Existing housing and buildings will make up ~75% of the 2050 building stock (Senate Canada, 2018).
- Today, natural gas, supplies ~75% of space & water heating for both housing and commercial buildings.
- Renewable electricity is generally not available when heating loads peak — cold winter nights.

CanmetENERGY-Ottawa, a research centre of Natural Resources Canada, is addressing the above challenges by strategically focussing research in:

- Improving the performance of existing buildings
- Designing and constructing new buildings that consistently perform at net-zero levels of performance
- Supporting the development and adoption of progressivly higher performing building energy codes, and
- Planning new and existing communities so that the built environment as a whole operates as a seamless system

All four research areas rely on computational tools and field validations that allow the identification of cost effective solutions for the retrofit of existing buildings, the design of new and the targetted interventions in the broader community.

## DECISION SUPPORT COMPUTATIONAL TOOLS

CE-O developed two computational tools to help with identification of optimised technoeconomically feasible approaches for building design and retrofit: the **Housing Technology Assessment Platform (HTAP)** adressing low rise construction (as per Part 9, NBC) and the **Building Technology Assessment Platform (BTAP)** adressing commercial and institutional buildings. The two tools use different simulation engines: HTAP uses HOT2000 (NRCan, 2008), while BTAP uses OpenStudio/Energy Plus (DOE, 2019) for energy simulation engines. However both tools use a similar structure to accomplish their objectives (Figure1).

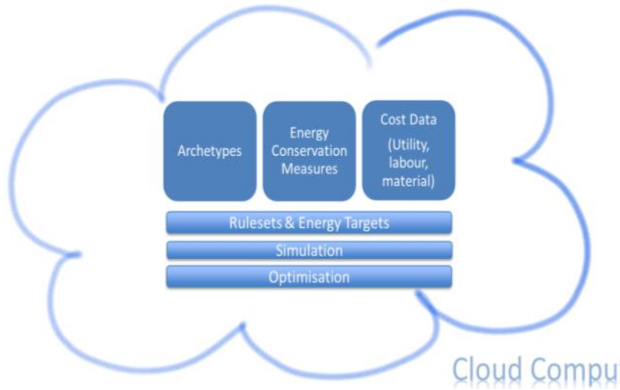


***Figure 1.*** *HTAP/BTAP Structure.*

The purpose of the tools is to examine energy, GHG and cost implications of design and retrofit options for housing and commercial buildings. In order to achieve these objectives, models (archetypes) that represent building typologies and vintages are used. The tools allow the users to substitute the energy impacting characteristics of the archetypes (envelope characteristics, mechanical systems, plugloads) in a programmatic sequential manner, providing the user the possibility of modeling thousands of houses/buildings in a relatively straightforward manner. Each model thus developed is coupled with the utility and capital costs of the jurisdiction for which they are formulated. Depending on the objective of the analysis, rulesets representing, for example, a code-compliant archetype, are applied and the differential cost, energy and GHG implications are generated for the baseline (the code-compliant archetype) and the optimised archetype.

Large-scale fast cloud computing facilitates large number of simulations required to arrive at the combination of energy impacting features that optimize the cost-benerfit for the building in question. The resulting large amount of data is displayed in easily interpretable visualizations tools.

## IMPROVING THE PERFORMANCE OF EXISTING BUILDINGS

### Envelope retrofits

When considering existing buildings deep retrofits are of particular interest, and more specifically the renovation to the building envelope. Heat loss through the envelope represents 2/3 of the energy use in a typical Canadian old home. Despite this, only 4% of retrofits conducted through NRCan incentive programs consisted of comprehensive building envelope performance improvements. The primary barriers to deep-energy enclosure retrofits include the high cost associated with the work, and the disruption that the work involves.

CE-O launched a project to directly deal with these barriers based on the use industrialized approaches to achieve net-zero energy (NZE) retrofits. The principles of Prefabricated Exterior Energy Retrofit (PEER) have been applied in an initial pilot (Figure 2) that achieved post retrofit airtightness of 0.89 ACH50Pa, and modelled heating consumption reduction of 64%.

The next stage in the development of the PEER concept is the application of the developed building capture and prefabrication technologies to a full scale pilot. The building in question is a row housing unit (Figure 3) owned and operated by the Ottawa Community Housing (OCH) (Carver et al, 2019), and the objective of the retrofit is to take this 1950's building to net zero energy performance level.

***Figure 2.*** *Pilot Retrofit at Bells Corners.*

***Figure 3.*** *OCH Full Scale Pilot in 2020.*

The first step in the development of the retrofit approach dealt with the evaluation of the available options: insulation levels for the foundation, walls and roof, air-tightness levels, window and door characteristics as well as domestic hot water and heating system performance levels. HTAP has been used to identify the most cost-effective combination of measures to reach the net zero level of performance and construction is slated to begin in the spring 2020.

### Retrofit optimization for the north

Retrofitting housing in the North deals with similar issues as anywhere else: improving home airtightness, increasing insulation levels, and replacing mechanical systems etc. The challenges however are significantly more complex: availability of materials, cost of labour, remoteness of location.

In order to develop a plan that addresses northern communities, HTAP was used to develop the options for the Yukon and North West Territories. The resulting selected options were then developed as an illustrated guide by RDH with the support of CMHC (RDH, 2017).

## DESIGNING AND CONSTRUCTING NEW HIGH PERFORMANCE BUILDINGS

In principle, designing and constructing high performing buildings, should not be a challenge given the studies demonstrating that such buildings can be built with little or no additional costs to the owners. However, a number of barriers appear when closer examination is applied. The first barrier is a result of the market competitiveness, resulting in limited time for engineers and architects to evaluate options that could meet high performance targets, and the lack of information on the performance and reliability of high performing equipment and systems and of their integration into high performing buildings.

### Cost-effective high-performing design options

Evaluating the design options is a time-consuming, labour intensive activity that few owners are willing to pay for and few design studios are equipped to carry out. In order to deal with this first market shortcoming, CE-O uses HTAP and BTAP to deal with the large number of simulations required to arrive at high performance solutions that are cost competitive.

The complexity of the issue of finding the options for a certain level of investment, is best illustrated by considering a relatively simple design problem of a single family home. When one considers, the different options available for a net zero home: air-tightness levels, insulation levels for the different envelope components, electro-mechanical systems, the designer has almost 300,000 options to select from. A large commercial building is several orders of magnitude more complex.

Figure 4 demonstrates an example of the application of the computational tools to evaluate the cost/benefit ration of the options.

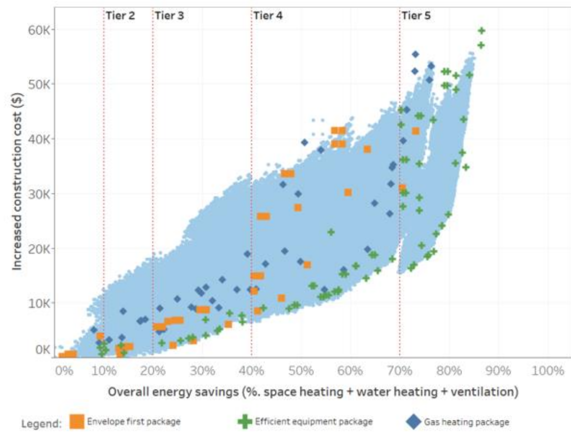


***Figure 4.*** *Cost implications of energy saving measures.*

In the above figure, each dot is a complete model of the house. The designer can readily see the desirable options very fast and select those that meet their cost and performance targets.

### De-risking innovative technologies

The second barrier to the design of high performing buildings is the lack of confidence in the performance of innovative technologies.

CE-O carries out laboratory and in-situ tests that lead to the development of guides for the industry (Sager, 2017) and that feed into the work that the LEEP team is doing to promote high peforming housing (NRCan, 2019).

- Hybrid heating system: The majority of homes in Canada are heated using natural gas, consequently the transition to non-emitting sources of heating is an important component of the puzzle associated with reaching the GHG emission targets. To this end, CE-O has tested the performance of hybrid systems, systems that combine natural gas-burning furnaes with heat pumps with the switchover between the two occurring when the utility cost the climatic conditions and the unit`s performance permit (Sager, 2020).
- In the commercial building sector, CE-O developed tools to facilitate the integration of passive technologies in the toolbox of designers. The earth tube tool, for example helps designers to select the characteristics of the tool for effective application in new construction (Brideau, 2018).

## DEVELOPMENT AND ADOPTION OF BUILDING ENERGY CODES

According to the Pan-Canadian Framework on Clean Growth and Climate Change (PCF), “federal, provincial, and territorial governments will work to develop and adopt increasingly stringent model building codes, starting in 2020, with the goal that provinces and territories adopt a net-zero energy ready model building code by 2030". To this end, CE-O applied the HTAP and BTAP tools to support Codes Canada in their efforts to develop the required justification and pathways to achieve net-zero energy ready level of performance in buildings and housing.

**Housing analysis**

HTAP has been applied to the development of the proposed housing tiered national building energy code. This activity applied the lessons learned from HTAP's application to the development of the British Columbia Step code (Province of British Columbia, 2017), and included considerations that are only possible due to the flexibility provided by the tool which was not available in previous code vintages.

As Proskiw (2011), there is a need to reflect regional weather, regional housing characteristics, costs and energy prices. In prior code development however, the use of HOT2000 limited the possible use of regionally representative archetypes, as the labour and computational costs would have been prohibitive. HTAP, as described above was develop to cope with the massive simulations required, and the first step in the analysis was the development of regionally representative archetypes.

CE-O developed a new set of 240 housing archetypes, representing detached and double/row new construction in major Canadian markets. The development relied on the approach developed as part of the Canadian Single Detached, Double and Row Database (CSDDRD) (Swan et al, 2009) development, and relied on data from the Energuide for Houses Database maintained by NRCan. The selection of the archetypes was informed by the Canada Mortgage and Housing Corporations's Housing Market Database and the Survey of Household Energy Use. The selected archetypes were sampled from actual homes built in Canada between 2015 and 2018 and have characteristics representative of the regional variations between major Canadian housing markets (Rasoul et al, 2019).

The arhetypes formed the basis on which a variety of energy conservation measures were applied coupled with costing and utility data. The results of the simulations formed the basis for the new tiered approach to the building codes for housing.

**Commercial building analysis**

CE-O developed rulesets in BTAP for 16 building archetypes that are compliant with the NECB2011, NECB2015 and NECB 2017 codes.

The developed platform was used to evaluate the impact of updating the code for Prince Edward Island, Nova Scotia and Manitoba from NECB2011 to NECB2015 or NECB2017. Based on the results of the analyses Nova Scotia adopted the NECB 2017 code.

CE-O guided National Research Council researchers on the use of BTAP in order to evaluate the impacts of moving NECB2017 to a tiered approach.

It should be noted that CE-O is closely collaborating with a number of academic and private organisations that use components and/or data generated by the Building Technology Assesment Platform in their research and development of related applications. These include the University of Victoria, Concordia University and Posterity.

## PLANNING COMMUNITIES

Two projects deal with community-level activities.

The Canadian Energy End-use Mapping (CEE Map) Project aims to help governments and utilities see housing energy end-use and efficiency opportunities as an additional layer on a map of the community, province or the country.

The initial CEE Map prototype is being developed in collaboration with the City of Kelowna, BC, built on the ESRI-based Model City developed by city staff. NRCan's CanmetENERGY-Ottawa and GeoAnalytics divisions will create the CEE Map prototype by adding outputs from the HTAP and BTAP platforms to characterize the residential use and efficiency opportunities in Kelowna's housing stock.

The Low Carbon Communities Energy Systems project builds on the recent Canadian district energy survey, and from the learnings from the Drake Landing Solar Community project and a net-zero community energy feasibility study conducted by CE-O. It focuses on what is required to accelerate the uptake of low carbon energy technologies on a community-wide scale. This project is leveraging on CE-O's knowledge on a wide range of clean technologies and our partnership with stakeholders in the community energy market in delivering research outputs that will inform policy makers, planners and community energy managers. The project aims at lowering barriers and to increase the uptake of low carbon community energy technologies in our existing communities.

## CONCLUSION

The paper addressed the research and development activities at CanmetENERGY Ottawa within the housing, buildings, and the community areas.

The teams at CE-O have developed a number of projects in close collaboration with academic and private organisations that expand the scope of the projects described in this paper to include issues related to electrification and embodied carbon considerations.

These projects, are at their initial stages of development and are closely linked with stakeholders that range from manufacturers, home builders, architectural and engineering firms, utilities and provincial and federal organisations.

The collaborative nature of the activities ensures that the developed technolgies, tools and analyses signficantly contribute to the broader Canadian efforts of improving the built environment and meeting the GHG emission reduction targets while maintaining and improving the competitiveness of Canadians.

## ACKNOWLEDGMENT

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à consommation nulle d'énergie

CAE Roadmap to Resilient Ultra-Low
Energy Built Environment with Deep
Integration of Renewables in 2050
Montreal Symposium, QC
October 16, 2020

# PASSIVE STRATEGIES TO IMPROVE MULTI-UNIT RESIDENTIAL BUILDINGS THERMAL COMFORT RESILIENCE IN FUTURE CLIMATE SCENARIOS

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## ABSTRACT

In Toronto, many of the thermally massive post-war multi-unit residential buildings (MURBs) do not have central cooling systems to mitigate overheating in summer weather. As the duration and severity of extreme heat events will increase in the future, these building occupants will be vulnerable to greater heat-related morbidity and mortality. Three passive strategies (overhangs, window films and interior roller shades) were simulated in an energy model of a 20-storey post-war MURB and compared against a base case model, to assess their impact on cooling energy consumption under current and future weather conditions. While the interior roller shades were found to be the single most effective measure at reducing cooling energy use, combining all three strategies yielded a 21.3% cooling energy reduction, as well as a 26.7% reduction in unmet cooling hours in the future weather scenario. In order to further reduce unmet cooling hours and address thermal comfort, active cooling systems are required.

## INTRODUCTION

Multi-unit residential buildings are a significant source of housing in urban regions, such as Toronto. As of 2016, about 44.3% of the dwellings in the City of Toronto are in apartment buildings with five or more storeys (City of Toronto 2019). However, many of the high-rise apartment buildings were designed with electrical or hydronic baseboard heating systems and are not equipped with central cooling systems. Therefore, the suites can only rely on natural ventilation, fans or packaged terminal air conditioners (PTACs) for cooling (CMHC 2017). As a result of global warming, it is anticipated that the outdoor temperature in Ontario will experience an average annual temperature rise of 2.5°C to 3.7°C by 2050, compared with the baseline average of 1961 to 1990 (MECP 2014). Rinner and Hussain (2011) found that Toronto, the largest urban area in Ontario consisting of dense high-rise buildings, has experienced a 1.6°C to 4°C higher surface air temerpature than the surrounding residential and open areas due to the negative impacts of the urban heat island (UHI) effect. Thus, natural ventilation and air movement driven by fans, which some studies have already shown to be ineffective, will not be an acceptable solution to overheating any more. However, before considering the implementation of active cooling, thermal comfort should first be improved by optimizing the building's passive features in order to minimize energy use. Studies have shown that passive strategies can effectively reduce solar heat gain in high-rise residential buildings. For example, research in Seoul, South Korea shows that the introduction of horizontal overhangs and roller shades results in cooling energy saving potential of 19.7% and 17.7%, respectively (Cho et al. 2014, Oh et al. 2018). Although there has been extensive research of passive strategies under current weather conditions, less is known about how passive strategies can perform under future weather conditions. This study aims to address this gap. This paper examines the effectiveness of passive strategies reducing the cooling load and number of unmet cooling hours in MURBs during summer months, under current and future weather conditions.

## METHODOLOGY

An archetypal post-war high-rise MURB was used as the subject of this study. The 20-storey rectangular building is a student family residence at the University of Toronto. It has a floor area of 28,730m$^2$ and is aligned along the east-west axis. The building has hydronic baseboard heaters and a pressurized corridor ventilation system. There is no central cooling but about one-third of the suites have PTAC units. Suite windows are double glazed with a low emissivity coating and thermally broken aluminium frames, and a window-to-wall area of 27%. Walls are made of concrete block with brick façade and drywall interior without insulation. The calibrated baseline model was generated in eQUEST (version 3.65.7173) by Touchie and Pressnail (2014), then each passive strategy was tested as part of the current study.

### Baseline Model

To assess the impact of the passive strategies on cooling energy consumption, PTAC units were added in all suites, and the total cooling capacity of PTACs required to meet the current cooling loads was auto-sized by eQUEST. For all the subsequent models, PTAC capacity was kept the same as in the initial baseline model to assess the number of unmet hours of cooling in each zone.

Each floor of the building was modeled with three zones: a south-facing A/C conditioned suites zone, a north-facing A/C conditioned suites zone, and a non-A/C conditioned corridor zone. Corridors are pressurized with un-conditioned outdoor air supplied by the rooftop air handling unit to meet the minimum ventilation air requirement for suite zones, therefore the corridor zone can be excluded from this study as it does not contribute to the cooling load. The suite cooling setpoint is 26°C, a health-based maximum indoor temperature in apartment buildings during cooling season as specified in Toronto Municipal Code. In order to assess how the building responds to the projected future weather, the energy simulations were run with both current and future weather files, which were historical Canadian Weather Year for Energy Calculation (CWEC) from 1959 to 1989 and future weather generated for the decade of 2040 to 2049 (2040s) by SENES Consultants Limited in 2011. Next, the energy model was run three more times to determine the cooling energy consumption for each passive strategy, and unmet hours in the north and south zones. For each hour that a thermal zone fails to maintain the cooling setpoint, one unmet hour is counted.

### Passive Strategies

Three passive strategies were selected for this analysis: overhangs, window films and interior roller shades. The overhang depth was obtained from an online tool developed by Sustainable by Design. Given the inputs of latitude (44°N), south-facing windows and window height of 2.0m (6.6ft), a chart of hourly heat gain from direct sunlight for any day during peak cooling month was generated. Overhangs with a depth of 0.76m (2.5ft) and an equal width to the windows where overhangs were installed right above, result in a minimal heat gain from direct sunlight at solar noon in July for south-facing windows. The adapted size of overhangs was also applied to north-facing windows to compare the change in unmet cooling hours between south- and north-facing zones. According to Ihm et al. (2012), it is beneficial to select glazing unit with low solar heat gain coefficient (SHGC) to reduce cooling energy load in MURB. But after-market window films can be an economical and feasible solution to reducing solar heat gain in a retrofit context. The commercially available interior films selected for this study can be directly applied to the interior side of the window to decrease SHGC from 0.67 to 0.44. Interior translucent roller shades were selected to allow some daylight in but also reduce solar gain. For the purpose of this study, the roller shades were assumed to be closed 100% of the time to maximize solar gain reduction. The input parameters of the selected passive strategies in our study are summarized in Table 1.

***Table 1.** Input Parameters.*

| PARAMETERS | INPUT VALUE |
|---|---|
| Overhangs | Depth of 0.76m (2.5ft), full window width, installed right above windows |
| Window Films | Total Window SHGC: 0.44, VT: 0.38, U: 0.69 Btu/h·ft$^2$·F |
| Roller Shades | Interior Translucent Roller Shades Openness: 3%, VT: 0.09 |

## RESULTS AND DISCUSSION

### Weather Comparison

Figure 1 compares the average monthly dry bulb temperature and relative humidity between the historical CWEC and 2040s Typical Meteorological Year (TMY) files. Figure 2 shows their corresponding monthly cooling degree days ($CDD_{18}$). As expected, the 2040s TMY features increased average dry bulb temperatures and thus increased cooling degree days.

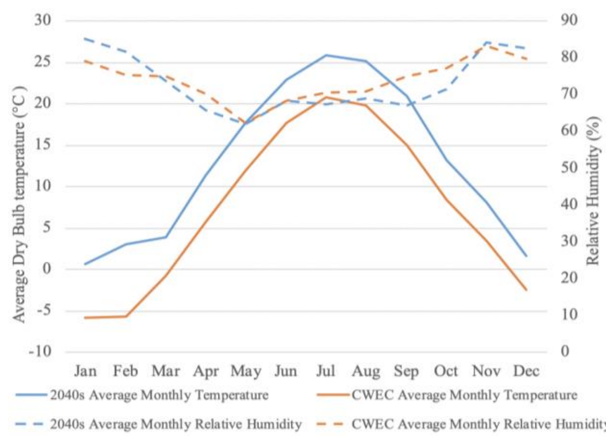



***Figure 1.** Average Monthly Dry Bulb Temperature and Relative Humidity.*

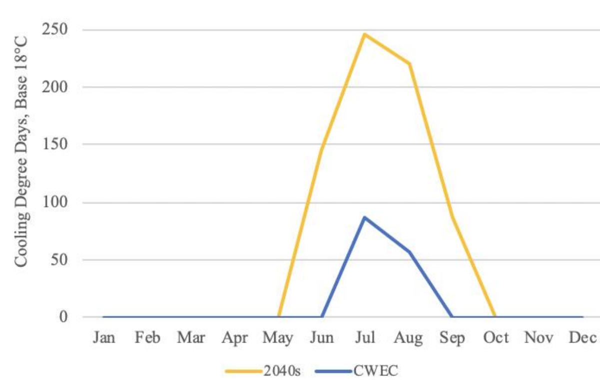



***Figure 2.** Monthly Cooling Degree Days.*

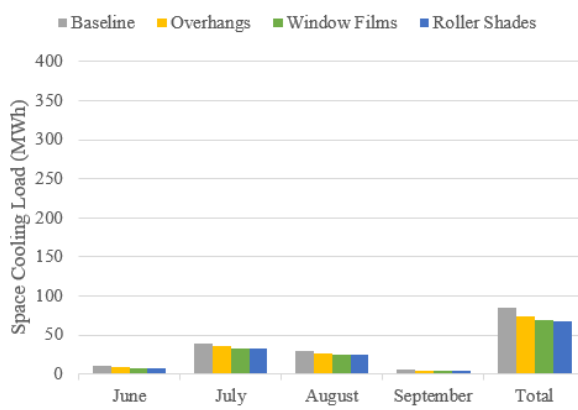
Table 2 compares the results of the base case model with the two different weather files and shows an increase in total cooling energy use intensity (EUI) and unmet cooling hours, as expected.

***Table 2.*** *Total Cooling Energy Use.*

| Weather File | Cooling Energy Use Intensity (kWh/m$^2$/yr) | Total Electricity (MWh) | Unmet Cooling Hours |
|---|---|---|---|
| CWEC TMY | 3.4 | 84.6 | 19 |
| 2040s TMY | 14.3 | 355.3 | 937 |

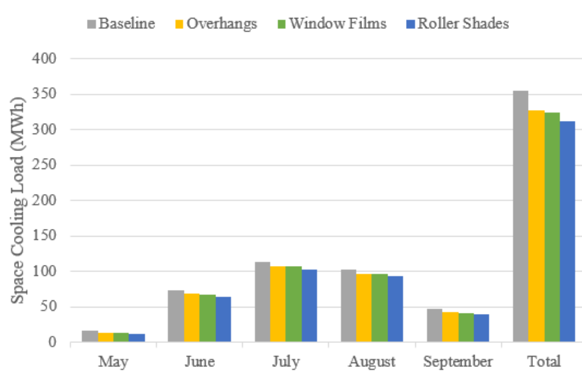
## Passive Strategy Comparison

Figures 3 and 4 summarize the monthly space cooling load of the baseline scenario and the passive strategies under current and future weather conditions.




| % Decrease from Baseline | June | July | August | September | Total |
|---|---|---|---|---|---|
| Overhangs | 15.5% | 9.0% | 13.6% | 20.4% | 12.2% |
| Window Films | 32.0% | 21.2% | 26.8% | 38.9% | 18.1% |
| Roller Shades | 23.3% | 14.2% | 19.2% | 29.6% | 20.2% |

***Figure 3.*** *Monthly Space Cooling Load (CWEC).*




| % Decrease from Baseline | May | June | July | August | September | Total |
|---|---|---|---|---|---|---|
| Overhangs | 20.7% | 7.2% | 5.6% | 6.7% | 11.4% | 7.9% |
| Window Films | 26.6% | 9.5% | 6.5% | 7.3% | 15.0% | 8.9% |
| Roller Shades | 24.9% | 8.7% | 5.9% | 6.7% | 13.9% | 12.1% |

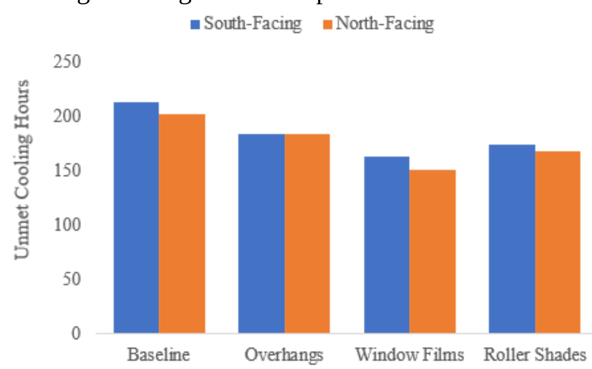
***Figure 4.*** *Monthly Space Cooling Load (2040s TMY).*

Among the three passive strategies, the roller shades reduce the cooling load most significantly by up to 20.0%, compared with the baseline result under current weather conditions, whereas the overhangs are the least effective strategy. However, roller shades can only reduce the summer cooling by 12.1% under future weather conditions. The change in effectiveness is because the cooling load under future weather file is significantly larger than it is under current weather file.

## Unmet Hour Comparison

For the future weather conditions of increased average dry bulb temperature, the auto-sized PTAC's cooling capacity in the current weather baseline model becomes inadequate to meet the cooling setpoint, which consequently, results in longer operation hours without mitigation of the overheating situation.

In the breakdown of the simulation results, the total number of unmet hours for each floor varies. It was found that Floor 19 has the highest number of unmet hours. Therefore, the 19$^{th}$ floor was further analyzed to illustrate the impact of each passive strategy on the total number of unmet cooling hours assuming future weather conditions. As shown in Figure 5, the unmet hours of the south-facing zones are greater than that of the north-facing zones. This is expected, as the south side of the building has a higher solar exposure.




| % Decrease from Baseline | Baseline | Overhangs | Window Films | Roller Shades |
|---|---|---|---|---|
| South-Facing | - | 13.6% | 23.4% | 18.2% |
| North-Facing | - | 8.9% | 25.1% | 16.7% |

***Figure 5.*** *Floor 19 Unmet Hours versus Input Parameters under Future Weather Condition.*

With the introduction of each passive strategy individually, unmet cooling hours for both south- and north-facing zones decrease; however, when comparing unmet hours between south- and north-facing zones, for example, adding overhangs to both zones result in a 13.6% decrease of unmet hours for the south-facing zone and a decrease of 8.9% for north-facing zone. Therefore, implementing passive strategies on the south side of the building is generally more effective to reduce overheating during summer, as expected.

### Combination of Multiple Input Parameters

As seen in Figures 3 and 4, implementing a single passive strategy under current weather conditions can ease overheating and reduce the cooling load by 12.2%, 18.1% and 20.2% using overhangs, window films and roller shades, respectively. However, implementing a single passive strategy under future weather conditions is not as effective (a maximum of 12.1% energy saving for roller shades). In order to improve the effectiveness of the selected passive strategies in reducing the cooling energy consumption under future weather conditions, we input all three parameters in one model to simulate a combined scenario. The cooling energy savings for each passive strategy and the combination of all three strategies are summarized in Table 3 as well as their corresponding percentage reduction of unmet hours.

***Table 3.*** *Summary of Energy Savings and Unmet Hours Reduction under Future Weather Condition.*

| Input Parameters | Total Space Cooling [MWh] | Unmet Hours | % Energy Savings | % Unmet Cooling Hours Reduction |
|---|---|---|---|---|
| Baseline | 355.3 | 937 | - | - |
| Overhangs | 327.1 | 874 | 7.9% | 6.7% |
| Window Films | 323.6 | 780 | 8.9% | 16.8% |
| Roller Shades | 312.2 | 833 | 12.1% | 11.1% |
| Combine Three Input Parameters | 279.5 | 687 | **21.3%** | **26.7%** |

As we can see from Table 3, combining all three input parameters results in a 21.3% cooling energy saving and a 26.7% unmet cooling hour reduction under future weather conditions. However, 687 unmet cooling hours indicates an unsatisfactory indoor environment and insufficient cooling capacity, therefore it is necessary to upgrade the existing PTAC system capacity or install other mechanical system such as heat pump to ensure indoor thermal comfort.

## CONCLUSION

Passive features of buildings can significantly reduce cooling energy consumption in summer and mitigate overheating. Three strategies, overhangs, window films and interior roller shades, were studied by running energy simulations of a post-war MURB in Toronto. The effectiveness of each strategy is relatively high under current weather conditions but lower under future weather conditions because of the increase in cooling load. Although improving building resilience by implementing multiple passive strategies can reduce cooling energy consumption, active cooling systems are still required to address thermal comfort in these buildings.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# BUILDING-INTEGRATED PHOTOVOLTAIC SYSTEMS: ENABLING ENERGY-RESILIENT HIGH-PERFORMANCE BUILDINGS

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## ABSTRACT

As Canada rapidly transitions toward net-zero and carbon neutral building performance targets through building codes, roadmaps and building rating systems, the on-site electricity generation will become compulsory. Building integrated photovoltaic are expected to be one of the main technologies to generate on-site electricity since they can be designed to virtually cover any building surface that has access to sunlight. This paper provides a brief overview of barriers that still hinder BIPV adoption in Canada and proposes actions to overcome them thus, enabling energy-resilient high-performance buildings.

## INTRODUCTION

While Canada is transitioning towards electrification and decarbonization of the building, energy and transportation sectors, its major cities struggle to mitigate and adapt to urban population surge and climate change. Currently, two thirds (27 million people) of the country's population live in census metropolitan areas. By 2050, it is projected that this number will rise to about 36 million people (Statistics Canada, 2019).

The urban population surge is expected to increase the net electricity and peak power demand in a somewhat predictable manner. On the other hand, the frequency, intensity and duration of extreme weather phenomena due to climate change creates a high uncertainty that extends beyond the increase of energy demand, to generation, operation and resilience of energy related infrastructure (Climate transparency, 2019; Perera et al., 2020).

Building-integrated photovoltaic (BIPV) are building envelope solutions that generate on-site electricity (and in some cases also thermal energy). BIPV can virtually cover any building surface (**Table 1**) turning buildings from energy consumers to energy prosumers. Considering that the major cities in Eastern Canada and the Prairies (e.g. Toronto, Montreal, Calgary, Edmonton, Ottawa, Winnipeg and Saskatoon) have solar potentials that are comparable to those of solar-leading countries (Figure 1), BIPV are expected to play a key role in the transition towards decarbonization and energy resilience of the building sector. This paper provides a brief overview of the primary barriers identified for the widespread adoption of BIPV in Canada and proposes steps to effectively overcome them.

## BIPV BARRIERS AND FACILITATORS

### Barriers perceived by solar and building industry professionals

In 2016, an independent survey (n = 50) was conducted on behalf of the Refined Manufacturing Acceleration Process (ReMAP) network, funded by the Business-Led Networks of Centres of Excellence (BL-NCE) program (Forum Research inc, 2016). The purpose of the survey was to assess the receptivity of the building industry in North America to BIPV window products, specifically.

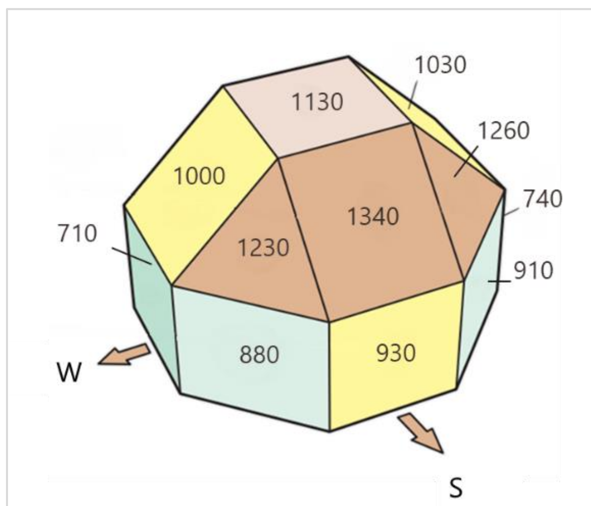



***Figure 1.*** *Potential annual electricity generation ($kWh_{AC}/kW_{DC}$) based on BIPV surface orientation and tilt angle, for Toronto (NREL, 2020). Routine or temporary shading is not considered.*

The survey identified the following primary barriers for the facilitation and acceleration of BIPV windows:

- lack of product/system familiarity and what this entails in terms of building design and installation;

- upfront cost; and,
- return-on-investment (ROI), with ROI be of greater importance than upfront cost when it comes to new constructions as compared to retrofit ones.

Interestingly, 57% of the respondents were likely to use BIPV windows in future projects while more than three-quarters (78%) would be willing to pay more than $21/ft$^2$ above that of energy efficient windows. Finally, most respondents reported that 10 to 15 years (70%) would be an acceptable time period for ROI.

In 2018, Natural Resources Canada conducted a consultation survey (n = 141) focusing on BIPV products at large, within the Canadian building and solar industry (Ebert and Kapsis, 2018). Like the ReMAP survey, the primary barriers identified for the widespread adoption of BIPV were:

- ROI;
- upfront cost; and,
- lack of design guidelines.

Overall, the optimism among respondents was strong with 98% of them being at least somewhat interested in using BIPV in future projects with the main motives being "green" (78%) and innovative (76%).

Similar studies have been conducted outside Canada indicating that some of the barriers hindering the uptake of BIPV are universal (Curtius, 2018; Heinstein et al., 2013; Lu et al., 2019; Shukla et al., 2018). The following section will try to address some of these barriers in Canada and when possible, propose actions to overcome them.

**Codes, standards and regulations**

The various organizations of international standards have recognized the multifunctional character of BIPV, the need to address both electrotechnical and building performance requirements and remove the risk from building owners and stakeholders. As a result, the first international BIPV standard is currently under publication, the IEC 63092. Modeled upon EN 50583 European standard (CENELEC, 2016a, 2016b), IEC 63092 is a two-part umbrella standard developed as a result of a liaison between Technical Committees (TC) IEC TC 82 and ISO TC 160. Part 1 of IEC 63092 describes BIPV module requirements while part 2 describes BIPV system requirements. Both parts address building and electrotechnical requirements, in general and specifically with respect to module assembly and application category (IEC, 2020a, 2020b). In addition, existing standards related to laminated glass in buildings are being revised to include BIPV.

The next necessary step to facilitate BIPV market acceptance is the Canadian adoption of the international standards. In addition, federal and provincial building, energy and fire codes need to be updated to allow for standardization and consistency in BIPV practices and safety. An extensive report on the requirements, specifications and regulations relevant to the development of BIPV performance and safety standards can be found under IEA PVPS Task 15 (Inoue and Wilson, 2019).

**Business models and policies**

Since 2008, the price of a typical crystalline silicon module in Canada has declined by more than 83% (Baldus-Jeursen et al., 2019). The price reduction is attributed to global market factors such as increase of cell efficiency, public and private R&D and economies of scale (Kavlak et al., 2018). At the same time, the country's installed capacity has increased from 32 $MW_{DC}$ in 2008 to 3095 $MW_{DC}$ in 2018, driven mainly by incentive programs in Ontario and Alberta. However, these factors had little impact on the price of BIPV and their widespread adoption in the building market.

While investment subsidies and feed-in tariffs related to BIPV can help and are welcome, Canadian BIPV industry needs to innovate by introducing new business models that:

- remove buildings owners' upfront cost;
- allow service providers to cost-effectively capture new value streams through proven BIPV solutions; and,
- create high confidence in BIPV performance and its financial returns.

Such business paradigms exist in other markets from which BIPV industry can learn from and adopt.

In recent years, the PV and building industries have been fueled by business model innovations that provide services to end users, rather than selling them products. Also known as "Product-as-a-Service" (BaaS) business model, BaaS allows service providers to tap into these multibillion-dollar markets and create new revenue streams by effectively selling energy savings rather than the equipment that delivers these savings – through power purchase agreements (PPA) for the PV industry and energy service performance contracts (ESPC) for the building one.

Similarly, the convergence of technological developments in BIPV have created an untapped business opportunity in industrial, commercial, institutional and high-rise residential buildings. Appropriate for both new and retrofit buildings, BaaS business model can also be used by the BIPV industry to decouple energy saving investments in buildings from buildings owners' upfront cost and ROI constrains. BaaS will be partly driven by the economies of scale (e.g. the added cost of BIPV is only 1-2 % of a commercial or institutional building cost), partly by the mandate to reduce energy consumption and peak power demand and partly by carbon tax policies (Canadian Ministry of Justice, 2020). Other BIPV business models exist (Macé et al., 2018). In all cases though, robust business models must cope without investment subsidies and feed-in tariffs.

**Research, development & technology demonstration (RD&D)**

While BIPV have reached technological maturity, RD&D (both public and private) will remain key drivers of BIPV cost reduction. In addition to the latest developments on coloured BIPV (Figure 2), new optically-smart laminates, films and coatings promise increased conversion efficiencies by harvesting near-infrared (NIR) photons or by down-shifting high energy ultraviolet (UV) photons through active photon conversion and plasmonic scattering (Eder, 2019; Jelle, 2016).

Polymer and perovskite tandem solar thin films are emerging PV technologies suited for BIPV window and skylight applications. With tunable transparency and colour, these new PV technologies use low-cost raw materials and low-cost, low-temperature (<120°C) and scalable manufacturing processes. However, further RD&D is necessary to overcome their lack of long-term stability. In addition, advancements in the laminated glass industry have allowed the manufacturing of curved BIPV modules.

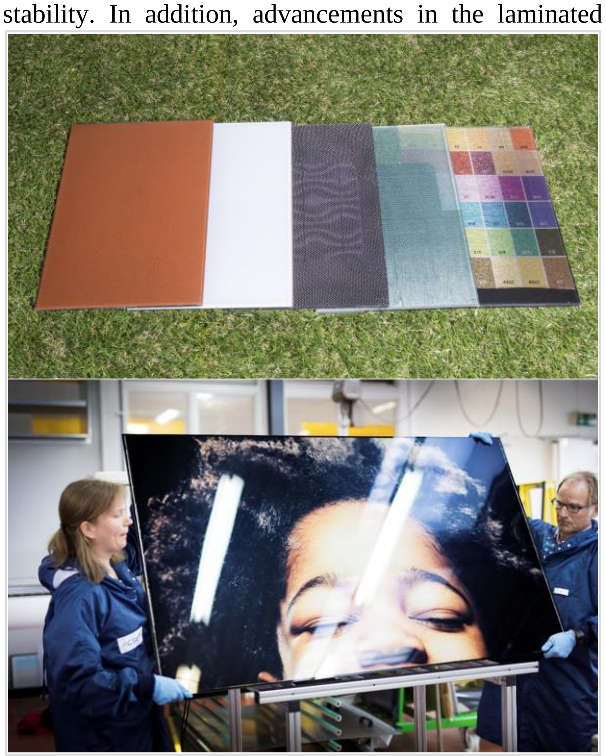


***Figure 2.*** *State-of-the-art coloured BIPV products redefine solar envelope aesthetics (Image credits – top to bottom: NRCan and Kaleo Solar, 2018).*

BIPV coupled with grid-interactive inverters and battery storage have enabled buildings to function in an isolated mode – when there is a power outage – or in a parallel-to-the-grid mode of operation (Figure 3). Treated as distributed energy resources (DER), these BIPV system configurations can also provide grid ancillary services at the request of the utility, thus, transforming buildings to an integral part of an energy-resilient, smart grid architecture (Kolokotsa, 2016).

Further RD&D is necessary to better understand the interactions of BIPV with the building HVAC, controls and operation (Kapsis et al., 2015; Kapsis and Athienitis, 2015), the energy storage, the power utility, and the transportation sector through electric vehicle (EV) energy transaction (Bhatti et al., 2016; Wu et al., 2016). It is only through interdisciplinary research collaborations, and integrated design and operation that the full potential of all these enabling technologies can be captured, providing safe, comfortable, efficient and affordable conditions in the built environment (Thomas et al., 2019). New advancements in the world of Building Information Modelling (BIM) and Internet-of-Things (IoT) also contribute to this direction (Gao et al., 2019; Mehmood et al., 2017; Minoli et al., 2017).

**Education of the building professionals**

While BIPV can benefit from the technological developments that take place in the solar industry, they are building products. As such, their price and market share are driven by building industry trends, and technological advancements specific to BIPV. However, it is a common mistake for BIPV to be compared (price- and performance-wise) with typical standard modules and systems used in PV farms, and building-added PV also known as BAPV (e.g. rooftop PV). The latter ones have a single function: to generate solar electricity. In the contrary, BIPV are multifunctional building envelope solutions that impact the building's:

- architectural aesthetics;
- mechanical resistance and durability;
- hygro-thermal and energy performance (heating, cooling and lighting); and,
- electricity consumption and its interaction with the power grid.

The BIPV multifunctionality (**Table 1**) and interoperability with the utility grid makes the realization of BIPV projects a challenging task. The current lack of technical knowledge between building professionals

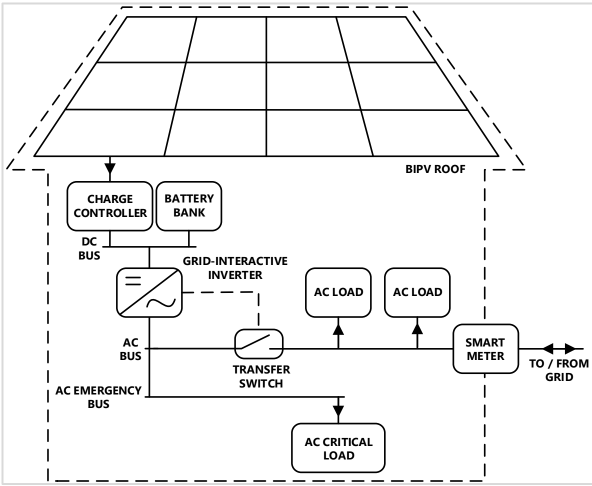



***Figure 3.*** *Grid-interactive BIPV application designed to continue operating during power outage (Credits: NRCan, 2018).*

(architects, engineers and consultants) on how to design and carry out BIPV projects is an additional barrier to the adoption of BIPV that should not be overlooked. Currently, there are national and international efforts to consolidate existing BIPV knowledge and disseminate it through continuing education courses, technical seminars and BIPV-specific technical guides (Eisenlohr and Illich, 2019).

The intent of a BIPV technical guide is to support the implementation of best practices and drive the decision-making process that could lead to an effective BIPV design as well as a resilient and robust BIPV installation while maintaining good architecture. BIPV shall be integrated into all phases of the construction process, from conceptual design stage, to construction, to operation and maintenance. Only this way, BIPV can evolve from a niche building technology to a mass market one.

## CONCLUSIONS AND OUTLOOK

A climate-resilient built environment is inheritably an energy-resilient one, able to mitigate and adapt to critical short-and long-term impacts. BIPV are expected to play a key role to the transition from a centralized carbon-intensive power generation to a distributed, resilient and renewable generation.

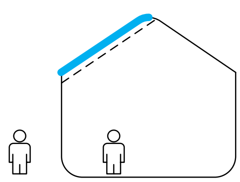
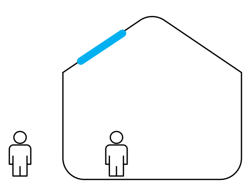
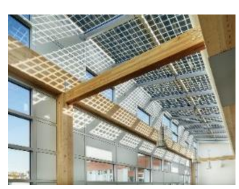
Recent technological advancements on coloured BIPV and power electronics have created new architectural opportunities allowing BIPV to virtually cover any building surface with access to sunlight (e.g. from roofs and walls, to windows and balcony balustrade).

Further BIPV R&D is necessary to assess and optimize BIPV coupled with storage for demand response, grid ancillary services and supply of on-site electricity for critical loads during extreme weather phenomena (e.g. ice storms, heatwaves and floods).

Greater coordination among all stakeholders and members of the BIPV value chain presents business opportunities for new revenue streams. Flagship building projects across the country can also help accelerate the market deployment and acceptance of BIPV (**Table 1**).

Finally, the Canadian regulatory framework and training of building professionals need to evolve accommodating BIPV envelope multifunctionality.

***Table 1.*** *BIPV application categories and performance requirements specific to each category, adapted from IEC 63092 standard.*

| BIPV Application Category | Pictogram of BIPV Application | Example of Canadian BIPV Application | Performance Requirements of BIPV Application |
|---|---|---|---|
| **Category A**<br>Roof-integrated, not accessible to the user from within the building.<br>e.g. gable roof, flat roof, shed roof |  |  | • Fire safety<br>• Mechanical resistance and durability<br>• Electrotechnical<br>• Hygro-thermal performance |
| **Category B**<br>Roof-integrated, accessible to the user from within the building.<br>e.g. skylight, atrium, canopy |  |  | • Fire safety<br>• Safety and accessibility in use<br>• Mechanical resistance and durability<br>• Electrotechnical<br>• Hygro-thermal performance<br>• Daylight and solar gains<br>• Protection against noise (if applicable) |

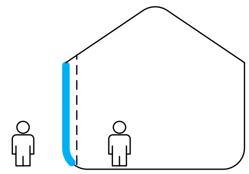
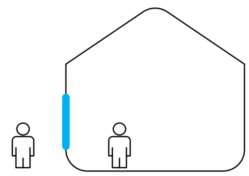
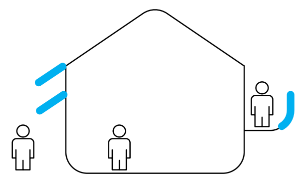
| | | | |
|---|---|---|---|
| **Category C**<br>Façade-integrated, not accessible to the user from within the building.<br>e.g. wall, rainscreen, curtain wall spandrel |  |  | • Fire safety<br>• Mechanical resistance and durability<br>• Electrotechnical<br>• Hygro-thermal performance |
| **Category D**<br>Façade-integrated, accessible to the user from within the building.<br>e.g. window, vision glass curtain wall |  |  | • Fire safety<br>• Safety and accessibility in use<br>• Mechanical resistance and durability<br>• Electrotechnical<br>• Hygro-thermal performance<br>• Daylight and solar gains<br>• Protection against noise (if applicable) |
| **Category E**<br>Externally-integrated, forming an additional functional layer of the building envelope.<br>e.g. balcony balustrade, sunshade, louvers |  |  | • Fire safety<br>• Safety and accessibility in use<br>• Mechanical resistance and durability<br>• Electrotechnical<br>• Daylight and solar gains (if applicable) |

Image credits (top to bottom): Maxime Gagné, Martin Tessler, Gordon Howell, One House Green and David Cigan

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# PROVIDING THE MAJORITY OF THE ENERGY NEEDS OF CANADIAN HOUSING BY SOLAR: THE NEED FOR SEASONAL STORAGE

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## ABSTRACT

The majority of the space and water heating needs of housing in cold climates can be supplied by solar energy, but only if long-term (seasonal) storage is employed to enable solar energy captured during the summer and autumn to be used during winter. This paper explains the necessity of seasonal storage for achieving high solar fractions, reviews the applications to date, and presents an experimental study on seasonal storage that is currently underway at Carleton University's Urbandale Centre for Home Energy Research.

## INTRODUCTION

Heating, cooling, and ventilating the places we live in, and providing the hot water, lighting, and appliance services we need, consumes tremendous amounts of energy. This contributes significantly to environmental and energy security issues. For example, housing accounts for 33% of all electricity and 24% of all natural gas consumed in Canada, and produces 13% of the country's greenhouse gas emissions (NRCan 2018).

In most cool and cold climates, space and water heating account for the majority of the energy demand in housing, and therefore offer the greatest potential for savings. If locally available solar energy could be exploited then the majority of these energy demands could be met in an environmentally benign manner. However, this is complicated by the strong seasonal mismatch between solar availability and space-heating needs. For example, in Ottawa approximately 85% of the solar energy resource is available outside the principle space-heating period (mid-November through mid-March).

## NEED FOR SEASONAL STORAGE

The potential of solar energy for providing the energy needs of housing can be seen in Figure 1. The left side of the figure displays the total energy needs of three average-size detached houses over the year. The *average* house represents the average energy consumption of the current Canadian stock of detached houses (NRCan 2018) while the *inefficient* house represents an older home that has not received substantial energy upgrades. The *efficient* house has insulation and airtightness levels beyond current code requirements and exceeds R-2000 levels of performance (NRCan 2012).

As can be seen, space and water heating demands dominate in all three cases. Even in the case of the efficient house, 44% of the total energy requirement is for space heating and 26% for hot water heating (70% of the total when combined). The remaining 30% of the energy needs are electrical and could be serviced by solar photovoltaics. However, solar thermal systems could more efficiently meet the 70% of the building's needs that are for low-grade heat.

The right side of Figure 1 illustrates the total amount of solar irradiance incident upon the opaque envelope of an average-size detached house (two-stories with a footprint of 75 m$^2$ and 30º roof pitch) over the year, assuming no shading by neighbouring buildings or objects. It can be seen that regardless of the building's orientation, the total solar energy incident upon the building greatly exceeds the energy requirements, even for the case of the inefficient house.

Contrasting the left and right sides of Figure 1 shows the potential for meeting the majority of a house's energy needs through solar energy, but the story is much more complicated due to intermittancy. This intermittancy issue is illustrated in Figures 2 and 3.

Figure 2 plots the solar irradiance to a 20 m$^2$ horizontal surface (size and orientation chosen for illustration purposes only) over two sunny winter days. It also plots the space heating demand of the average house for these days. As can be seen, the space heating demands are lowest around solar noon when passive solar gains are highest, and highest during the night. Conventional solar thermal systems employ diurnal storage—usually in the form of water tanks of a few hundred litres located in the

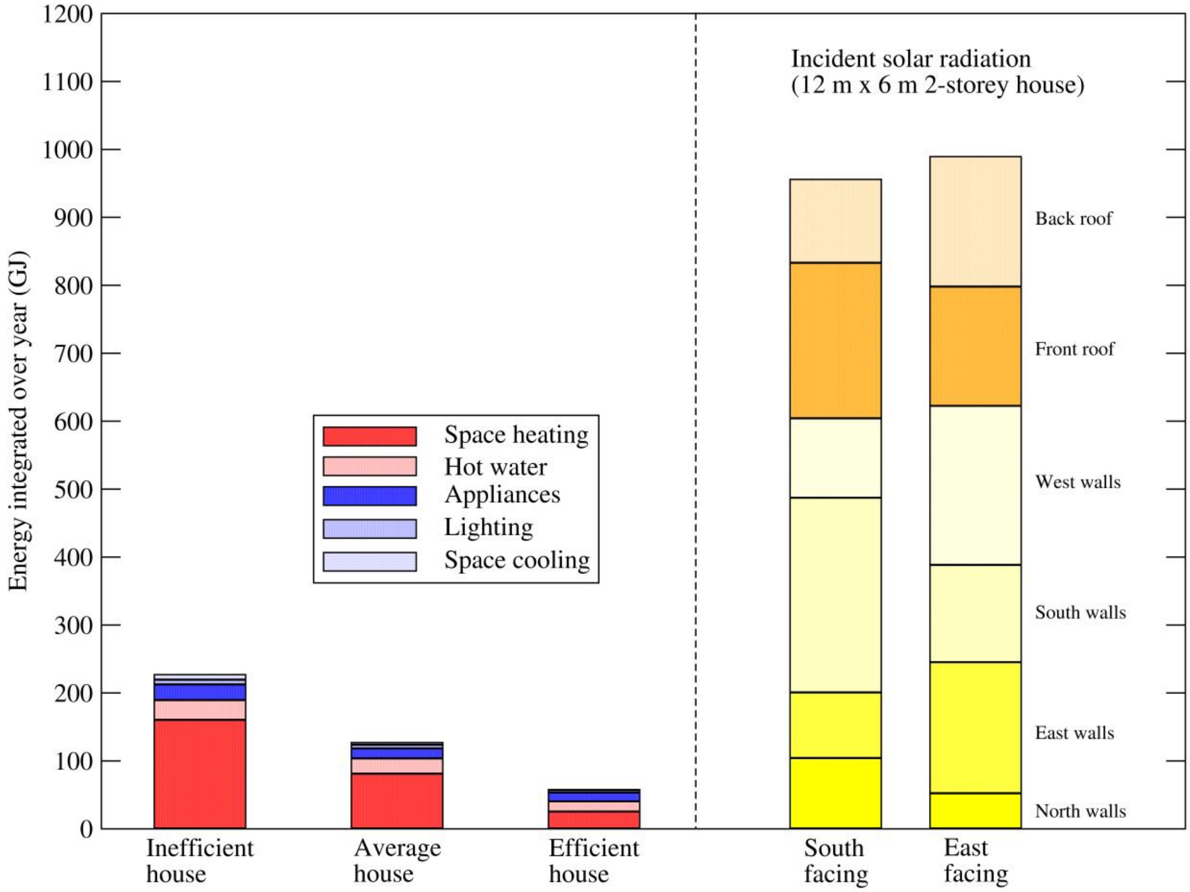


***Figure 1.*** *Annual energy demands vs solar resource.*

basement—to buffer between this type of mismatch. Such systems can store energy from several hours to a couple of days. In practice they rarely achieve solar fractions greater than 50% (Edwards 2014).

The more significant mismatch between supply and demand is seasonal rather than diurnal. This is illustrated in Figure 3, which plots weeky integrated amounts of the same quantities. The preponderance of the solar resource during the summer period is clearly seen. The figure also shows that the vast majority of the space heating demand—which accounts for the majority of the building's total energy demand—occurs from mid-Nomber to mid-March. An integration of these two curves reveals that only 15% of the year's solar resource is available at this time when the building's needs are greatest.

For these reasons it is clear that high solar fractions can only be achieved if the solar resource from the summer can be captured and stored for use during the winter.

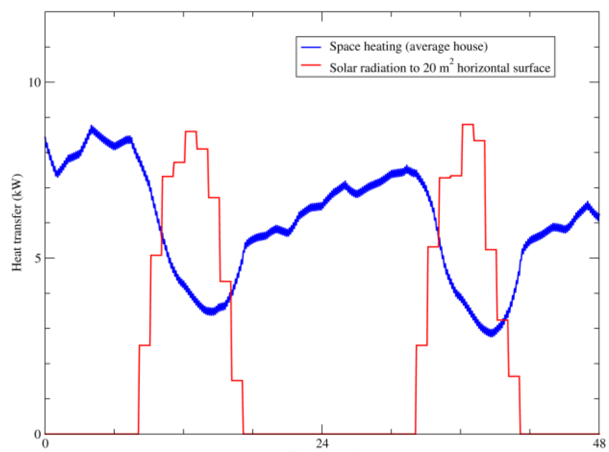


***Figure 2.*** *Diurnal mismatch between supply and demand.*

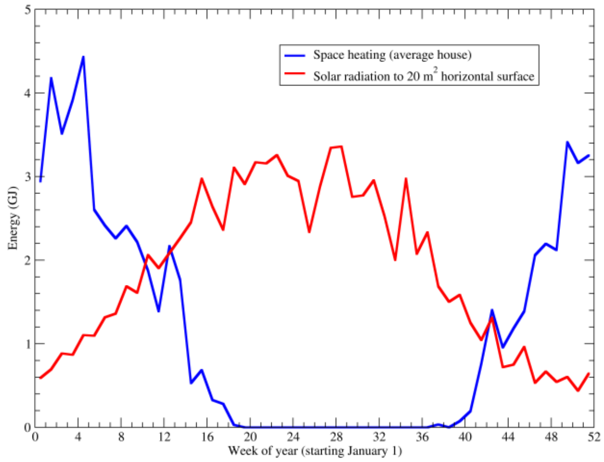


***Figure 3.*** *Seasonal mismatch between supply and demand.*

## SEASONAL STORAGE OPTIONS

Pinel et al. (2011) and Xu et al. (2014) performed extensive reviews of options for seasonal storage of solar thermal energy. The storage mechanisms can be broadly classified as sensible, latent, and chemical (reactions or sorption). Sensible storage relies upon the temperature rise of a medium; latent takes advantage of energy stored and released during a phase transition; and chemical methods make use of reversible endothermic/exothermic reactions.

Latent and chemical storage options offer considerable potential to reduce storage volumes and to reduce heat losses. Although some early applications of chemical storage have been reported (e.g. Köll et al, 2017), as stated by both Pinel et al. (2011) and Xu et al. (2014) these technologies are still in their infancy (at least from an economic perspective). For this reason, most of the seasonal storage applications to date have relied upon sensible storage.

Most applications of solar seasonal storage reported in the literature have been for district or community-scale systems. Ochs et al (2009) report on more than 30 such systems, with an emphasis on tank and pit sensible storage with volumes ranging between 300 and 12 000 $m^3$. In an earlier study, Dalenbäck (1990) reviewed eleven district plants installed in Europe and Canada. These employed several different sensible storage methods, including earth (borehole) storage, insulated tanks, rockpits, and aquifers. Mesquita et al. (2017) report on a community-scale system that serves 52 single-family detached houses. The system is composed of flat-plate solar collectors with a 240 $m^3$ short-term water-based sensible store and a large borehole field for seasonal sensible storage in the soil. According to Furbo et al (2018), as of 2016 there were 110 solar district systems operating in Denmark, with a combined collector (mostly flat plate) area of 1.3 million $m^2$.

Although heat losses from the seasonal stores have exceeded expectations in many cases, some of these community-scale systems have achieved high solar fractions for space heating, in some cases exceeding 80-90%.

Most applications of solar seasonal storage have been with community-scale systems because specific storage costs decrease with volume (Pfeil & Koch 2000). Notwithstanding, some authors (Kroll & Ziegler, 2011) have argued the benefits of building-scale systems based upon simulation studies and have shown that the prejudice against such small-scale systems is unfounded. The density of many residential neighbourhoods makes building-scale seasonal storage, despite its higher specific storage costs, an attractive alternative to community-scale systems because of reduced losses from transmission networks due to the proximity between building-mounted solar collectors and the seasonal store. Reduced capital costs for the transmission network and land demands for community-scale stores are other factors to consider.

In another recent simulation-based study, Hsieh et al (2017) examined possible storage options and found that decentralized building-scale systems could outperform centralized community-scale systems, at least for solar fractions in the range of 40% to 50%. Their findings also highlight the importance of having separate diurnal and long-term (seasonal) stores, and that the design and control of the system can have a significant impact upon performance. The development and testing of commercial building-scale seasonal storage tanks employing vacuum insulation is discussed in Fuchs & Hofbeck (2014).

A few experiments have also been conducted on solar seasonal storage at the scale of single-family detached houses. Köll et al (2017) examined the performance of an adsorption storage system in a scaled laboratory experiment in which building thermal loads were mimicked. Evacuated tube collectors were used to charge the seasonal adsorption store and a diurnal water store. They achieved a total solar fraction of 83.5% for the Austrian case they examined. Most other building-scale applications (Besant et al. 1979; Esbensen & Korsgaard 1977; Clarke et al 2014) have employed sensible storage using water.

## DESIGN OPTIONS FOR CANADIAN HOUSES

A full-scale experiment of a solar thermal system with sensible seasonal storage has been designed, built, and commissioned at the Urbandale Centre for Home Energy Research located on the Carleton University campus to further the knowledge of seasonal storage at the single house scale for Canadian housing.

The system (see schematic in Figure 4) includes both diurnal and seasonal thermal stores, which can be charged independently or concurrently by the roof-mounted evacuated-tube solar thermal collectors. DHW loads are met by the diurnal store, while space-heating loads are met through a hydronic radiant floor distribution system by drawing hot water from either the diurnal or the seasonal store.

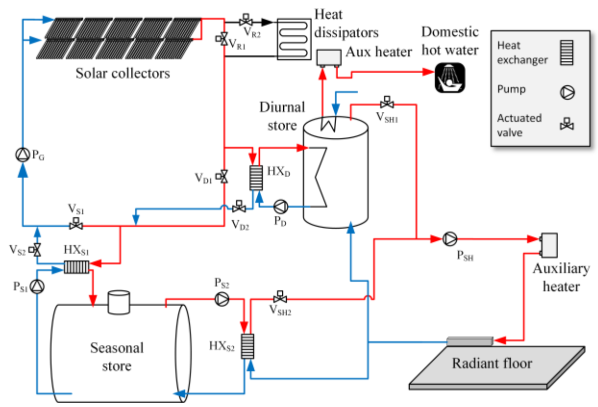


***Figure 4.*** *Configuration of solar thermal system with diurnal and seasonal storage.*

The diurnal store is located within the house's basement while the seasonal store is buried next to the house. The seasonal tank is of cylindrical shape with rounded ends and has an interior diameter of 3 m. It is fabricated of a fibreglass reinforced plastic resin that has a long-term temperature tolerance of 93 °C. Spray-on polyurethane insulation was applied to the tank to a thickness of 30 cm, and this was protected with another layer of fibreglass reinforced plastic to prevent moisture and structural damage to the insulation. Figure 5 shows the tank located in the ground next to the house's basement, prior to its burial.

***Figure 5.*** *Seasonal store in ground next to basement of unfinished house.*

The diffuser inlets and outlets—which are designed to encourage thermal stratification within the tank—as well as thermocouple monitoring ports can be seen on either side of the centrally located access hatch in the figure.

Based upon a detailed simulation study this system design is expected to achieve an overall solar fraction (space and hot water heating) over the year of 85-90%.

A second seasonal storage system composed of an insulated box of saturated sand has also been fabricated (Figure 6). This is under investigation as an alternative to the tank storage system. Future experiments may also investigate an adsoprtion based seasonal storage system.

***Figure 6.*** *Sand based seasonal storage system.*

## CONCLUSION

The majority of the energy needs of Canadian houses is for space and water heating. Although future building codes will require greater levels of envelope insulation and airtightness, the importance of these low-grade energy demands will continue. Therefore, solar thermal is an indispensible technology if we aim to deliver the majority of housing energy needs through solar energy. This paper shows that seasonal storage is a necessary component for a solar thermal system that achieves a high solar fraction. This paper outlines the possibilities for seasonal storage, and then describes ongoing experiments investigate sensible technologies at the single-house scale.

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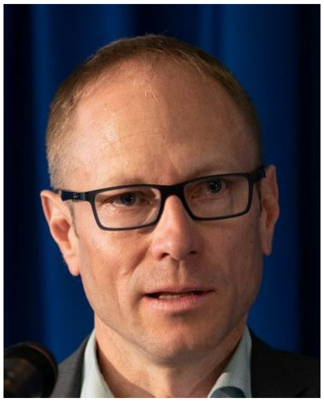
**Miguel F. Anjos, FCAE**, holds the Chair of Operational Research at the School of Mathematics, University of Edinburgh, and an Inria International Chair. He is the Schöller Senior Fellow for 2020 at the University of Erlangen-Nuremberg. His research interests are in the theory, algorithms and applications of mathematical optimization. He is particularly interested in the application of optimization to problems in power systems management and smart grid design. He is the Founding Academic Director of the Trottier Institute for Energy at Polytechnique, and President-Elect of the INFORMS Section on Energy, Natural Resources, and the Environment. He served on the Mitacs Research Council since its creation in 2011 until 2017 and is now an Emeritus member. His accolades include IEEE Senior Membership, a Canada Research Chair, the NSERC-Hydro-Quebec-Schneider Electric Industrial Research Chair, the Méritas Teaching Award, a Humboldt Research Fellowship, the title of EUROPT Fellow, and the Queen Elizabeth II Diamond Jubilee Medal.

**Dr. Andreas K. Athienitis, FCAE**, is a Professor of Building Engineering and Director of the Centre for Zero Energy Building Studies at Concordia University. He holds the NSERC/Hydro Québec Industrial Research Chair "Optimized Operation and Energy Efficiency: Towards High Performance Buildings" and a Concordia University Research Chair. He is a Fellow of the Canadian Academy of Engineering, Fellow of IBPSA and Fellow of ASHRAE. He obtained a B.Sc. in Mechanical Engineering (1981) from the University of New Brunswick and a PhD in Mechanical Engineering from Waterloo (1985). He led as Principal Investigator the NSERC Smart Net-zero Energy Buildings Strategic Research Network and the NSERC Solar Buildings Research Network with over 30 researchers from 15 Canadian Universities and about 30 industry and public sector partners. He was profiled as one of 25 top innovators in Québec by Actualité Magazine. He has published over 300 refereed papers, including seven that received best paper awards, and several books. He played a leading role in the conception and realization of several award-winning innovative buildings such as the Varennes net-zero energy Library. He is currently co-chair of the Canadian Academy of Engineering Roadmap to Resilient, Ultra-Low Energy Built Environment with Deep Integration of Renewables in 2050.

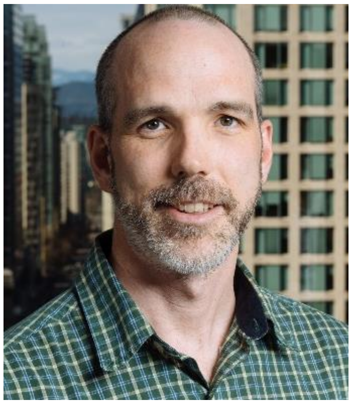


**Andrew Pape-Salmon, FCAE**, is an adjunct professor with the University of Victoria. Over the past twenty years Andrew has worked with two provincial offices for building and safety standards and energy efficiency. He also worked as a consulting engineer with RDH Building Science, with the City of Vancouver and the Pembina Institute. He specializes in sustainable energy systems, conservation and efficiency, energy and building sector economics and policy, and most recently resilient communities with an interest in seismic risk mitigation.

**Dr. Chris Kennedy, P.Eng., FCAE**, joined UVic in 2016, to chair a new ‘green’ Civil Engineering department, after 18 years at UofT. He conducts research on sustainable cities, biophysical economics and the industrial ecology of global infrastructure. Has been a visiting professor at Oxford University and ETH Zürich; and a seconded to the OECD. Chris is a former president of the International Society for Industrial Ecology; a member of the Global Cities Institute at UofT; and a member of UVic’s Institute for Integrated Energy Systems.

Professor **Ursula Eicker** is the new Canada Excellence Research Chair (CERC) for Next Generation Cities at Concordia University Montréal. A German physicist, Eicker has held leadership positions at the Stuttgart University of Applied Sciences and its Centre for Sustainable Energy Technologies. She coordinated many international research projects in the fields of energy efficiency in buildings and sustainable energy supply systems for more than two decades.

Since June 2019, she leads an ambitious research program to establish transformation strategies toward zero-carbon cities. The 7 year research program receives 10 million CAD government funding and is supported by a further 10 million Dollars by Concordia University, who invests in the city cluster research with five professor positions in buildings and electrical engineering, biodiversity, philosophy and design. The Concordia Next Generation Cities Cluster addresses the challenges of the urban transformation with a transdisciplinary approach and develops tools and strategies for a sustainable future. She has published 7 Books, 23 book contributions, 77 Peer Reviewed Papers and 317 Conference Papers.

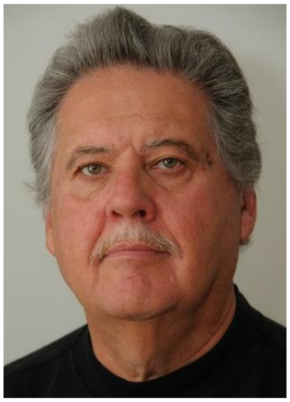


**Rémi Charron, Ph.D., P.Eng.**, has over 15 years of experience working to improve energy efficiency and integrate renewable energy on buildings in Canada. He has been working as a senior research and education consultant with BC Housing since 2012. In that role, he has been helping the building industry adapt to the continuously evolving building code requirements. He is also working as an Assistant Dean and Associate Professor for the Master of Science in Energy Management at NYIT-Vancouver.

**Dr. Caroline Hachem-Vermette** is an associate professor at the University of Calgary, School of Architecture, Planning and Landscape. Her research area includes the investigations of multifunctional energy-efficient, resilient neighborhood patterns, solar potential and energy implications of building shapes, building envelope design, developing multifunctional facades for multistory buildings, and others. Her research is multidisciplinary, it plays a bridging role between building engineering and architectural and urban design. She is currently leading a subtask on developing strategies for net-zero energy solar communities, within the International Agency Energy Task (IEA) 63- Planning Solar Neighborhoods. She was also an expert on 2 others IEA tasks on solar energy in architecture and urban planning. She is widely published on the topic of energy efficiency and solar energy, including a book (with Springer) on designing solar buildings and neighborhoods. Dr. Hachem-Vermette is a recipient of a number of awards including the 2019 Peak Scholar Award, 2016 sustainability award, e-sim/ IBPSA award for innovation in modelling, and Hangai prize for young researchers.

**Theodore (Ted) Stathopoulos, FCAE**, is currently Professor at Concordia University, Montreal, Canada. His research in the area of wind effects on buildings and their codification has been influential in the development of codes and standards around the world. He has an extensive publication record with more than 500 articles in refereed journals and conference proceedings. He is a member of the ASCE 7 Committee on Minimum Wind Loads and the respective committee of the Canadian Code. He is a Fellow of the Canadian Academy of Engineering, the Institution of Civil Engineers and the American Society of Civil Engineers and its Structural Engineering Institute. He is the Editor of the Journal of Wind Engineering and Industrial Aerodynamics. He has been appointed Distinguished Professor in Building Physics, Urban Physics and Wind Engineering by the Technical University of Eindhoven, The Netherlands He has received an Honorary Doctorate from the Aristotle University of Thessaloniki, Greece; and another one from the Technical University of Eindhoven, The Netherlands.

**Dr. Rosamund Hyde** is Stantec's Manager of Research and Innovation Services. She holds two degrees in Mechanical Engineering and a doctorate in Civil Engineering, and is licensed as a Professional Engineer in British Columbia and Ontario. After teaching in Canada and working in development in rural Nigeria for three years, she completed her advanced degrees and entered the consulting industry as a sustainable building researcher in 2001. For the past 14 years she has led the growth of research resources for Stantec consultants, managing internal research-related tax savings programs. She established and manages the Stantec R&D Resource eLibrary to make up-to-date technical literature available to Stantec employees worldwide in support of their evolving design work; in the past 10 years, downloads have grown to more than 30,000 articles per year. Dr. Hyde has been active in post-occupancy evaluation of green buildings in Canada, and served on the Canadian Engineering Accreditation Board for 6 years.



**Ted Kesik** is a professor of building science in the John H. Daniels Faculty of Architecture, Landscape and Design at the University of Toronto with a career focus on the integration of professional practice, research and teaching. His current research involves the development of design guidelines for low-carbon buildings that are resilient, sustainable and promote climate change adaptation. Dr. Kesik continues to practice as a consulting engineer to leading architectural offices, forward thinking enterprises and progressive government agencies.

**Dr. Iain A. Macdonald** is a senior researcher and team lead of the Integrated Building Performance group at the Construction Research Centre of the National Research Council (NRC), Canada. He is currently the technical lead for the Net Zero Energy Research project which is developing the supporting evidence to enable net-zero energy ready building codes for Canada.

**Liam O'Brien, Ph.D., P.Eng.,** is an Associate Professor in Civil and Environmental Engineering at Carleton University. He is the principal investigator of the Human Building Interaction Lab, which consists of a team of 15 researchers with diverse backgrounds in engineering, architecture, and psychology. His team is developing occupant-centric design processes, building code, and controls for high-performance buildings. He has authored over 150 publications and two books on this topic. He is a co-Operating Agent of IEA EBC Annex 79: Occupant-Centric Building Design and Operation and the past president of the Canadian chapter of the International Building Performance Simulation Association.

**Louis Gosselin** is a full professor at the department of mechanical engineering at Université Laval. His work mainly focuses on energy efficiency in buildings and industries. He has supervised various research projects based on building monitoring and optimization. The work shown in this presentation consists in the PhD project of second author Jean Rouleau (now a research assistant for Prof. Louis Gosselin). It was part of the NSERC Industrial Research Chair on Eco-responsible Wood Construction (CIRCERB) and realized through a partnership with the Société d'habitation du Québec.

**Dr. Chang-Seo Lee** is a Research Associate and Part-time Faculty in the Department of Building, Civil and Environmental Engineering at Concordia University in Montreal, Canada. As a Professional Engineer in Ontario, she has an extensive experience in academic research and industrial projects in the areas of building environment, HVAC, air quality, air purification and odor control technologies, and environmental health and safety. Current areas of interest and activity include research and development of advanced air cleaning systems, modeling and development of photocatalysts, evaluation of ozone monitoring technologies and abatement systems. She is actively involved in ASHRAE Technical and Standard Committees including TC2.3, TC2.9 and SSPC145. At Concordia University, she teaches Building Science, and Indoor Air Quality & Ventilation.

As R&D Manager, **Meli Stylianou** is responsible for a team of researchers and engineers involved in research leading to the development of technologies as well as innovative tools that support the national energy codes as well as the implementation of these technologies for the design and retrofit of housing and buildings.

Prior to his current responsibilities, he was the Acting Director for the Renewables and Integrated Energy Systems, and as such was responsible for research programs in Wind, Marine and Solar Energy as well as in Integrated Energy Systems applied to housing and buildings.

He led the Canadian team in the International Energy Agency's Annex 25 developing the first diagnostic tools for high performance buildings and developed and presented material to the Canadian consulting engineering industry that led to the adoption of new ways of tuning commercial buildings.

He has been an invited speaker to a number of industry forums and is the recipient of ASHRAE's Willis H. Carrier as well as the AQME Energia awards.

He is currently the Canadian representative on the IEA Energy in Buildings and Communities Technology Collaboration Program.

**Marianne Touchie** is an Assistant Professor jointly appointed in the Departments of Civil & Mineral Engineering, and Mechanical & Industrial Engineering at the University of Toronto. In her Building Energy and Indoor Environment (BEIE) Lab, Dr. Touchie's research team focuses on improving the energy performance and indoor environmental quality of existing buildings to make them more comfortable, healthy and sustainable through comprehensive retrofits. This work includes field monitoring of building energy performance and indoor environmental parameters as well as occupant behaviours and perceptions through surveys. Much of her research has been in the high-rise residential sector and particularly social housing buildings. Dr. Touchie is also the President of the Building Science Specialist Board of Canada and the Chair of ASHRAE's Technical Committee 2.1 of Physiology and Human Environment.

**Costa Kapsis** is an Assistant Professor in the Department of Civil and Environmental Engineering at the University of Waterloo. His research is focused on questions of energy efficiency, solar energy generation and energy transaction in the built environment. These research efforts aim towards the evolution of (i) building envelope technologies, (ii) climate-resilient cities and communities and (iii) energy integration between the building and transportation sectors. Costa serves as an associated editor of the Architectural Engineering journal and co-leader of the IEA PVPS Task 15 Subtask C on the development of Building Integrated Photovoltaic (BIPV) technical guidelines.

**Ian Beausoleil-Morrison** has worked for the past 13 years at Carleton University, where he is a professor in the Faculty of Engineering and Design. Prior to moving to academia, he worked for 17 years at CanmetENERGY on building energy efficiency, principally on the development of building energy models and simulation tools. He recently published a textbook on the fundamentals of building performance simulation, has authored 44 articles in peer-reviewed journals in the past 6 years and has delivered conference keynote talks in Japan, Italy, the UK, the USA, and Canada, as well as appearing as a witness to the Standing Senate of Canada's Committee on Energy, the Environment, and Natural Resources. He is a past president and Fellow of the International Building Performance Simulation Association, and co-founded and co-edits the Journal of Building Performance Simulation, one of the top-ranked journals in construction and building technology.

**Marianne Armstrong** is Director of Stakeholder Engagement and Management with Canada's National Research Council (NRC) Construction Research Centre. In her current role she is managing research in support of Provincial and Territorial priorities for building codes, as well as engaging key stakeholders in the transformation of the current National codes system. From 2016-2019, she managed the Climate Resilient Buildings & Core Public Infrastructure initiative to integrate climate resiliency into Canadian building and infrastructure codes, standards and guidelines. For over a decade, Ms. Armstrong also conducted residential energy efficiency research at the Canadian Centre for Housing Technology, where she helped to assess the performance of over 60 different housing technologies. Ms. Armstrong is a member of the Professional Engineers of Ontario, holds a MSc Industrial Design from University of New South Wales, Sydney, and a BSc Mechanical Engineering from Queen's University.

**Christian Bélanger** joined Hydro-Quebec’s Research Institute in 2016. He is currently Director of Research, Strategic and Cross-Functional Projects. In this role, he is responsible for the partnerships and the corporate technology vision in relation to this Direction.

Prior to joining Hydro-Quebec, Mr. Bélanger worked in Research & Development in various organizations in the chemical, materials and automotive sectors, in Europe and Canada. He has extensive experience in innovation management in both the public and private sectors.

Mr. Bélanger received his Ph.D. from McGill University in Chemical Engineering in 1992 and his engineering degree in Physical Engineering from École Polytechnique de Montréal in 1986. He owns an EMBA from Concordia University.

**Bryan Purcell** is the Vice President of Policy and Programs at The Atmospheric Fund (TAF), an award-winning public agency dedicated to addressing climate change in the Greater Toronto and Hamilton Area, and a founding member of the Low Carbon Cities Canada partnership administered by the Federation of Canadian Municipalities. Bryan’s work focuses on accelerating decarbonization through development of innovative policies, programs, and business solutions. Bryan has been instrumental in designing and implementing a range of climate solutions, including TAF’s non-debt Energy Savings Performance Agreement which has been used to finance major energy retrofits in over twenty buildings housing over 2500 households. Bryan played a key role in the development of the Toronto’s Transform TO Climate Plan and the Toronto Green Standards for new construction, and advises cities around the region on climate policy and programs including through the Durham Community Energy Plan Steering Committee.

**Sophie Hosatte-Ducassy** has been working for Natural Resources Canada (NRCan) since 1992, at CanmetENERGY research center located at Varennes, Quebec, focusing on developing and implementing clean energy solutions, and building on knowledge that helps produce and use energy in ways that are more efficient and sustainable. She has been the Director of the Buildings Group managing over 35 researchers and engineers in advancing the development of renewable heating and cooling technologies as well as optimizing building operations. The group is also involved in several deployment initiatives on behalf of other government departments advancing the Science and technologies priorities of the Government of Canada. For instance, it provides technical support to federal departments to help them meet their GHG emission reduction targets in the Greening Government Operation initiative; a strong established collaboration with DND and DRDC for many years to help them reduce their diesel consumption, in particular for their mobile camps. The results raised interest from the NATO Science for peace and Security Program and the Canadian Red Cross, with which collaborations are in place.

Sophie Hosatte has been representing Canada in several international, multilateral research groups including the International Energy Agency Heat Pumping Systems Technology Collaboration Program, which she chaired from 2004 to 2014, as well as the Mission Innovation - Innovation Challenge #7 on Affordable Heating and Cooling. Sophie holds an engineering diploma and a Ph.D. in Mechanical Engineering, from France.